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# The Effect of Leaves and Steel Support Cables on The Dynamic Properties of Northern Red Oak (*Quercus rubra*) with Co-Dominant Trunks

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**THE EFFECT OF LEAVES AND STEEL SUPPORT CABLES ON THE  
DYNAMIC PROPERTIES OF NORTHERN RED OAK (*QUERCUS RUBRA*)  
WITH CO-DOMINANT TRUNKS**

A Thesis Presented

by

MARK E. REILAND

Submitted to the Graduate School of the  
University of Massachusetts Amherst in partial fulfillment  
of the requirements for the degree of

MASTER OF SCIENCE

September 2013

Environmental Conservation

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## **ABSTRACT**

### **THE EFFECT OF LEAVES AND STEEL SUPPORT CABLES ON THE DYNAMIC PROPERTIES OF NORTHERN RED OAK (*QUERCUS RUBRA*) WITH CO-DOMINANT TRUNKS**

September 2013

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Natural frequency and damping ratio were measured for ten forest grown northern red oak trees with co-dominant trunks. Steels support cables were installed in the canopies of five of the sample trees prior to measurement. Free vibration testing was performed during periods when leaves were and were not present. An accelerometer mounted at the base of the co-dominant union measured the acceleration time history during the free vibration testing. Natural frequency was determined from the acceleration time history using power spectral density analysis. Damping ratios were calculated from the power spectral density plots using the half power bandwidth method.

Trees with steel support cables had higher natural frequencies than trees without steel support cables. Sample trees had higher natural frequencies in the leaf off condition than the leaf on condition. The increase in natural frequency associated with the steel support cable was less pronounced in the leaf on condition. There was no difference between the damping ratios of cabled and non-cabled trees. Trees in the leaf on condition had significantly higher damping ratios than trees in the leaf off condition.

## TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS .....	iv
ABSTRACT .....	v
LIST OF TABLES .....	vii
LIST OF FIGURES .....	viii
 CHAPTER	
1. INTRODUCTION .....	1
Background .....	1
Role of Urban Forests .....	1
Urban Tree Risk Management .....	4
2. LITERATURE REVIEW .....	8
3. MATERIALS AND METHODS .....	18
Study Site and Sample Selection .....	18
Free Vibration Testing .....	19
4. RESULTS .....	27
Frequency .....	27
Damping Ratio .....	29
5. DISCUSSION .....	31
6. CONCLUSION .....	48
 APPENDICES	
A. ACCELERATION VS TIME HISTORY AND POWER SPECTRAL DENSITY PLOTS .....	50
B. ACCELERATION VS TIME HISTORIES WITH DECAYING EXPONENTIAL FUNCTION .....	91
C. MORPHOLOGICAL AND MEASURED CHARACTERISTICS OF SAMPLE TREES .....	112
LITERATURE CITED .....	113

## LIST OF TABLES

Table	Page
1. Morphologic characteristics of northern red oak ( <i>Q. rubra</i> ) trees used for free vibration testing. Mean values with standard error in brackets .....	18
2. Morphologic characteristics of northern red oak ( <i>Q. rubra</i> ) trees used for free vibration testing after removing the two inadequately excited trees. Mean values with standard error in brackets .....	27
3. ANOVA table for mixed effects model of (a) frequency and (b) damping ratio .....	28
4. Morphologic measurements of sample trees used by Milne, Baker, Kane and James, and this study. Mean values with standard errors in parentheses .....	34

## LIST OF FIGURES

Figure	Page
1. The Cadwell Forest Urban Forestry Research Plot is located in western Massachusetts within the town of Pelham, in Hampshire County.....	19
2. Hardware installation in sample tree.....	21
3. The hardware configuration for pulling and releasing the sample trees .....	24
4. The attachment of the tensioning rope to the pull rope .....	25
5. Interaction plot of frequency by cable treatment and leaf condition .....	28
6. Box plot of damping ratio by leaf condition.....	30
7. Frequency by leaf condition.....	34
8. Simulated frequency distributions for tree components .....	39
9. PSD plots for sample tree in Leaf Off condition. ....	40
10. PSD plots for sample tree in Leaf On condition. ....	40
11. Dynamic response factor for cabled (red) versus non-cabled (blue) trees.....	43
12. Dynamic response factor for trees in the leaf off condition (red) and leaf on condition (red).....	43
13. Scatter plot and best fit lines for the Leaf Off: No Cable (green), Leaf On: No Cable (blue) and Leaf Off: Cable (red) frequency groups .....	46

# **CHAPTER 1**

## **INTRODUCTION**

### **Background**

An urban forest includes the same natural components that make up a rural forest: vegetation, water, soil, and wildlife resources. The fundamental difference is that urban forest resources occur in densely populated areas and adjacent lands (Cordell, 1979). In 2000, approximately 3% of the land area of the co-terminous United States was considered urban, but approximately 80% of the population lived in such areas (Nowak et al., 2010). The percentage of the population residing in urban areas is projected to increase to 85% by the year 2025 (McPherson, 2006). As urban areas become more concentrated population centers, the management and conservation of urban forestry resources will become more important and necessary to maintain the benefits they afford to the population.

### **Role of Urban Forests**

Trees comprise a large proportion, and are often the most easily identified type of vegetation in an urban forest. Urban trees account for approximately one quarter of the total canopy cover in the lower 48 United States (McPherson, 2006). The trees in an urban forest provide numerous tangible and intangible benefits to urban residents as well as the urban ecosystem.

Some of the benefits of trees within an urban setting are easy to quantify while others have a more abstract value. Though not necessarily monetary, almost all would agree that most trees in the urban setting have a positive value (Franks & Reeves, 1988). The degree to which trees are valued usually varies among individuals. Hall (1981)

found that, in general, people assume one of three viewpoints towards trees in the landscape:

1. Trees are inanimate objects similar to rocks and man-made structures.
2. Trees are living organisms but separate from an ecosystem.
3. Trees are a component of a larger, overall natural system.

The viewpoint an individual holds greatly influences their perception of the benefits urban trees provide.

The benefits include, but are not limited to: aesthetic beauty, community identity, human stress reduction, energy and water conservation, wildlife habitat and biodiversity, and enhanced property values (Hull, 1992). Urban trees can also help amend severely disturbed urban soils (Nowak et al., 2010), modulate the microclimate within urban areas (Nowak et al., 2010)(Franks & Reeves, 1988), and improve air quality (McPherson, 2006). Some of these benefits are more easily demonstrated and quantified than others.

Two of the more easily quantifiable benefits that urban trees provide are enhancing property value and reducing energy consumption. Morales (1980) concluded that: 1) tree cover was one of eight significant variables that influenced the sale price of property, 2) trees in residential areas were usually valued and 3) such trees provide a considerable array of other benefits. However, specific monetary values for individual trees within the observed areas were not included, only their influence on the final sale price. Laband and Sophocleus (2009) concluded that owners of residential and commercial properties located in hot climates experience considerable monetary savings from shade trees that naturally complement air conditioning (Laband & Sophocleus,

2009). In Beauregard, Alabama annual savings due to reduced cooling energy consumption of shaded buildings exceeded \$500 (Laband and Sophocleus, 2009).

Despite success quantifying the value of urban trees with respect to property values and energy consumption, quantifying the monetary value of individual trees has proved difficult. Methods of valuation have included a traditional stumpage value, or value of the timber a single tree would yield, values based on the cost of replacement of the tree, and other methods that attempted to incorporate property and landscape value to individual specimens. In a review of valuation methods, Kielbaso (1979) highlighted the difficulty in assigning monetary values to individual trees in the urban landscape with examples demonstrating how different evaluators arrived at widely varying values for the same tree. Franks and Reeves (1988) supported this notion and outlined the complex nature of benefits provided by urban trees. In particular, as Hall (1981) previously noted, value is perceived differently among different audiences. For example, trees lining a shady residential street are worth more to residents than their value as timber (Franks & Reeves, 1988).

Trees in the urban forest also provide intangible benefits that are harder to quantify. Dwyer et al. (1991) hypothesized that psychological ties between people and trees defy easy quantification, noting that trees within the urban forest influence urban residents in ways more complicated than visual aesthetics. Previous studies had also demonstrated that individuals given views of urban vegetation had slower heartbeats and lower blood pressure than individuals given views of urban settings devoid of vegetation (Ulrich, 1981).



Additional evidence of the complex relationship between urban residents and trees within the urban forest has been observed following natural disasters that severely altered the state of the urban forest such as hurricanes, tornadoes, snow and ice storms, and insect infestations. In a survey study performed after Hurricane Hugo affected Charleston, SC in 1988, Hull (1992) found that 30% of survey respondents identified the urban forest as the physical feature most special to them and felt it was the most significant feature damaged by the storm.

The special affinity residents of urban areas feel for trees have been hypothesized to be rooted in a sub-conscious feeling within urban residents of trees as being enduring or resilient in nature (Dwyer et al., 1991). This sub-conscious feeling was further explained by a view of urban trees as living, breathing organisms (Dwyer et al., 1991); an observation that aligned with Hall's (1981) findings concerning the general classification of urban residents' views towards trees within the urban forest.

Though their value may be hard to quantify, it is apparent that many urban residents value and desire urban trees in the landscape. Urban trees, and the urban forest as a whole, require management to ensure continued longevity. This management encompasses many aspects including site management, water management, nutrient and soil management, and management of risk and hazards associated with urban trees.

### **Urban Tree Risk Management**

Because of the peculiar circumstances in which they grow, urban trees are subjected to many stresses not experienced in a traditional forest stand. Tattar (1984) observed that a large proportion of the decline and death in an urban forest is the direct result of human activity and is therefore predictable and preventable. Schwarz and

Wagar (1988) further explored this concept and concluded that preventative measures can substantially reduce the cost of urban tree management.

Although residents value trees, they are also concerned with tree failures, which can damage property and injure people. This is especially true in residential areas where large, mature trees are located in close proximity to structures. It is not possible to eliminate the risk posed by trees in urban areas; some level of risk must be accepted to experience the benefits that trees provide (Smiley et al., 2011). Tree risk management is the application of policies, procedures, and practices used to identify, evaluate, mitigate, monitor, and communicate tree risk (Smiley et al., 2011).

There are two broad categories of risk that are encountered when managing trees in an urban setting: conflicts and failures. Conflicts arise between trees and societal functions and include, problematic flowers, unpleasant odors, interference between branches and road signs or communication lines, and sidewalk and street damage caused by root systems (Smiley et al., 2011). Failures include the breakage of stems, branches, roots, or the loss of mechanical support from the root system (Smiley et al., 2011). Conflicts can be greatly reduced by selecting the right tree species for a particular planting site, pruning to avoid interference with vital infrastructure, and involving the community and a qualified arborist when planning to plant trees. Appropriate arboricultural management (e.g., pruning and installing artificial support systems) can also reduce the number of tree failures. Artificial support systems commonly employed in urban trees are the focus of this study.

In the previous section the benefits of trees in the urban forest were described in order to emphasize their vital role in urban settings. These benefits increase as the age

and size of trees increase (Smiley et al., 2011). Compared to a smaller canopy, a larger canopy will intercept more precipitation and solar radiation. The former more effectively reduces storm runoff (Hull, 1992), while the latter results in a larger influence on surrounding microclimate (Franks and Reeves, 1988). A larger canopy also provides more leaf area, which increases the intake and filtering of particulate matter (McPherson, 2006).

As trees mature they are also more likely to shed branches or develop decay or other conditions that can predispose it to failure, regardless of their size (Smiley et al., 2011). This trait is of particular concern in urban areas where people, property, and activities could be injured, damaged or disrupted as a consequence of tree failure (Smiley et al., 2011). The consequences of failure can prove much more costly through lawsuits and property damage than the preventative treatments that could have been employed to prevent them (Schwarz & Wagar, 1988; Mortimer and Kane 2004). Urban tree risk management strives to strike a balance between the risk an urban tree poses and the benefits it affords the surrounding community (Smiley et al., 2011).

The multitude of stresses that affect urban trees can lead to their decline and death and contribute to an increased level of risk. Clark and Matheny (1991) stated that increased longevity of urban trees requires specific investment in chemical and structural defenses, and were able to document three main causes of the decline and death of trees in the urban forest:

1. Structural Failure
2. Environmental Degradation
3. Parasitic Invasion

They further advised arborists to employ two main methods to help facilitate increased longevity; develop a stable environment for the tree, and develop a stable physical structure for the tree (Clark and Matheny, 1991).

Developing a stable physical structure for the tree will help to reduce the likelihood of structural failures in the future. Any tree, whether it has a visible weakness or not, will fail if the forces applied exceed the strength of the tree or its parts (Smiley et al., 2011). Forces in excess of a tree's strength are commonly generated by winds during tornados, hurricanes, and even bad thunderstorms as well as dead load accumulation due to heavy snowfall, freezing rain, and ice. Structural weaknesses such as mechanical damage, decay, and poor branch attachments serve to lower the strength of the tree and make it more susceptible to structural failure.

However, there are treatments commonly employed by arborists to counteract structural defects in urban trees. The treatment of interest is the use of artificial support systems within the tree to supplement the natural strength of the wood. This includes installing bracing rods in weak unions to reduce the likelihood of failure as well as installing cables between canopy elements to provide additional support to weak or co-dominant branch attachments. The implementation of cabling, bracing, and other artificial support systems provide additional support to canopies (Clark and Matheny, 1991). The objective of this study was to determine the effect, if any, of static steel support cables on the natural physical parameters of a tree as determined through free vibration testing.

## **CHAPTER 2**

### **LITERATURE REVIEW**

The literature pertinent to this study encompasses tree physiology and growth form, cabling methods and techniques and their resultant impact on tree health, and vibration analysis. Literature related to tree physiology and growth form will be presented first, followed by literature related to cabling methods, and finally literature related to vibration analysis.

Environmental factors have a large impact on the final growth form a tree will assume. Wade and Hewson (1979) used trees as a biological indicator for regional wind profiles based on the examination of individual growth form characteristics. The characteristics that Wade and Hewson examined are attributed to an attempt to minimize the adverse effects and losses during extreme wind events. Additional weather events have an impact on tree form as well.

Cannel and Morgan (1989) found that ice and snow accumulation on tree branches may increase their weight by up to 12 times. It was also observed that fine branching pattern, structural weaknesses, and higher degrees of lateral branching were associated with a greater incidence of ice damage (Cannel & Morgan 1989; Hauer et al. 1993). Trees with high degrees of lateral branching have more surface area exposed for ice accumulation than trees with lower degrees of lateral branching. This was observed indirectly as deciduous angiosperms, which generally exhibit higher degrees of lateral branching, seem to be generally more susceptible than conifers to ice storm damage

(Hauer et al. 1993). It was also noted that strong winds increase the potential for damage from ice accumulation (Hauer et al. 1993).

It is not only during severe weather events that structural weaknesses and poor growth form are of concern. Greco et al. (2004) re-iterated that trees with multiple leaders, a common characteristic of trees of decurrent form, are susceptible to breaking and pose a threat to nearby structures as well as people and overall tree health. Smiley observed that the most common location for the above ground portion of a tree to fail is at the junction of two or more co-dominant stems (Smiley 2003). Arborists and urban foresters need to be acutely aware of this threat and manage any risk that a tree poses. Current standards in arboriculture aimed at managing trees at risk rely on flexible steel cables that are installed within a tree crown to limit excessive movement and reduce stress within a weak union (Smiley et al. 2011).

Empirical data have supported the conventional wisdom regarding branch attachments (Matheny and Clark 1991). Gilman (2003) found that the strength of branch attachments in juvenile red maples (*Acer rubrum* L.) was inversely proportional to the ratio of branch diameter to trunk diameter, although the coefficient of determination varied from 0.25 to 0.90, depending on the branch diameter. In a similar study, Kane et al. (2008) found that this same ratio, as well as the ratio of inside bark diameter to width of attachment were the best predictors of breaking stress of branch attachments of red maple, sawtooth oak (*Quercus acutissima* Caruthers), and Bradford pear (*Pyrus calleryana* Decne var. 'Bradford'). The authors cautioned that an attachment where the branch to trunk diameter ratio is greater than 70%, should be considered half as strong an attachment that includes a clearly subordinate branch (Kane et al. 2008).

Tests of larger trees have found similar results to studies on smaller trees (Gilman 2003; Kane et al. 2008). Kane and Clouston (2008) found that failure of co-dominant stems occurred at half the compressive stress of failures of single stems. In the study, co-dominant failures occurred at 45% of wood strength while stem failures occurred at 79% of wood strength (Kane and Clouston 2008).

The findings of Kane and Clouston (2008) supported Smiley's (2003) conclusions on the effect of included bark on the strength of co-dominant stems of red maple: unions with included bark were 20% weaker than unions without included bark when the stem diameter was 10 cm and 14% weaker when the stem diameter was 25cm. The relatively small reduction in breaking strength observed due to included bark led Smiley (2003) to caution that all co-dominant stem unions should be considered weak; and that remedial treatments should be applied when a target was present. Drenou (2000) also observed while classifying branch unions that a union with enclosed bark often seemed weaker than unions without enclosed bark.

In addition to hazardous branches, structural defects within the tree are potentially important factors contributing to a failure (Edberg & Berry 1999). Much of the research in the structural characteristics of trees has been performed with respect to weather induced stresses such as snow and ice accumulation and high wind speeds.

Proper structural development in trees begins when the tree is a sapling. Harris et al. (1972) describes the proper training of young trees necessary to develop their inherent structural strengths and ability to withstand the elements. The common practice of using stakes and guying material to provide additional support on newly planted saplings is described as detrimental to a trees development of a sound structure. Trees that are not

staked and have to withstand wind stress immediately after planting develop shorter trunks of larger caliper, greater trunk taper, and canopies more evenly distributed up the trunk that are better able to withstand the elements without support (Harris et al., 1972).

Niklas (1993) described the forces experienced by trees as they increase in size. The susceptibility of stems and roots to mechanical failure increases as the tree increases in mass or height. Gravity serves to compress stems and cause cantilevered branches to bend under their own weight while the load the stem experiences increases in proportion to growth increase (Niklas 1993). Additionally, by elevating leaf surface area higher above the ground the drag forces generated by wind pressure increase (Niklas 1996). Niklas stated that individual organ morphology and tissue material properties vary in accordance with the degree of mechanical perturbation (Niklas, 1993), which is in agreement with Harris' findings that unstaked trees were better able to withstand environmental stresses more quickly after planting (Harris et al. 1972).

The consequences of poor tree structure are the breaking off of crown parts and large branches. Branches become weakened because of poor structural characteristics or decay and are unable to withstand loading by wind, ice, or snow accumulation. This results in branch or crown failures because the weak spot developed to the point that it was unable to support the weight beyond it (Shigo 1989).

Cabling and bracing are two methods used by arborists to mitigate tree risk. The purpose of a cable installed within the canopy of a tree is to help the tree, not support it (Hamilton & Marling 1981). The cable is placed in the canopy to aid the tree during times of high stress, such as during snow and ice storms and extreme wind events, not to support the tree or parts of the canopy during periods of low stress. Initially, variations in



the manufacturing of support system components and a high degree of uncertainty associated with artificial support systems necessitated written specifications and policies for their installation to protect from liability (Mayne 1975). The necessity for regulation led to the creation of the American National Standards Institute (ANSI) standard on artificial support systems for trees and woody plants (Anonymous 2006).

Early research on artificial support systems investigated suitable components for use and how to properly install them. Jeffers and Abbots (1979) found that preformed helical dead ends were quicker to install and broke at more than the rated strength of the extra high strength cable. The helical dead ends were tested against the traditional method of hand-splicing the cable onto the mounting hardware in the tree. Smiley et al. (2000) found that placing brace rods a short distance above a co-dominant union offered greater strength than placing the brace rod directly through the union. This research was based on previous observations that v-shaped co-dominant stem junctions were weaker than the stems directly above them and often the site of failure (Smiley et al. 2000). Additionally, the authors cautioned that whenever possible, cables should be used in conjunction with brace rods in order to reduce movement in the co-dominant union (Smiley et al. 2000).

Incidence of decay and other adverse effects of installing hardware associated with support systems have also been investigated. Felix and Shigo (1977) found that the size, depth, position, and number of holes placed in the tree during hardware installation determined the degree of injury sustained by the tree. The authors advised that smart hardware placement would minimize the injury to the tree and maximize the benefits of a cabling or bracing system (Felix and Shigo 1977; Shigo and Felix 1980). It was found

that holes placed into decayed wood caused the decay to spread to surrounding wood while holes placed into healthy or discolored wood caused little injury (Felix & Shigo 1977). Kane and Ryan (2002) found that discoloration and decay directly attributable to hardware installation were not as severe as expected while examining samples visually and with simple measurements. Kane and Ryan (2002) also suggested that more quantitative research into the physiological and mechanical aspects of tree support systems is needed to assess each system's utility for arborists.

Recent research into mechanical aspects of tree support and crown characteristics has focused on trees response to wind stress. However, much of the tree-wind literature has not appeared in tree care publications resulting in arborists and urban foresters having a limited understanding of the forces and underlying concepts involved during tree-wind interactions (Cullen 2002).

Duryea et al. (1996) found that hurricane force winds affected tree species differently in Miami after Hurricane Andrew. A survey study showed that native species were more resistant to hurricane winds than exotic species, most notably native dicots (Duryea et al. 1996). It was also noted from the survey that pruning was associated with a reduced incidence of failure in some species (Duryea et al. 1996).

Smiley and Kane (2006) found that pruning significantly reduced wind load on trees while testing juvenile red maples. The authors also noted that bending moment, not drag alone, determines the mechanical stress on trees (Smiley & Kane 2006). Gilman et al. (2008a) found that pruning dose and treatment reduced trunk movement of live oaks subjected to wind velocities equivalent to those in hurricanes and tropical storms (Gilman et al. 2008b). It was found that crown reduction pruning and thinning significantly

reduced upper trunk movement at all wind speeds, whereas raising did not. It was also found that lower trunk movement was not affected by pruning type (Gilman et al. 2008b). It was concluded that pruning reduces potential damage during wind events (Gilman et al. 2008b).

The wind resisting features of canopy design have also been investigated in order to better understand how trees respond to wind stress. Vogel (1996) found that leaves reconfigure and curl to form hollow tubes during wind events and uncurl and lay flat during calm periods. Cullen (2005) hypothesized that foliar reconfiguration during wind events effectively reduces the sail area and decreases the overall wind load experienced by the tree. This led to a reconsideration of the conventional drag equation where wind load is dependent on wind velocity squared. The foliar reconfiguration dictates a velocity exponent between 1 and 2, however, the conventional exponent of 2 is most appropriate for estimating wind load during risk management or urban and landscape trees (Cullen 2005).

Trees are modeled as flexible structures while attempting to identify the mechanisms they employ to dissipate stress (Vogel 1996; James 2003; Cullen 2005; Kane et al. 2009). While investigating rigging operations commonly employed in arboricultural operations, Kane et al. (2009) documented with strain response and video evidence that trees respond dynamically by oscillating during rigging operations. James (2003) observed tree structure loaded by highly variable wind gusts and the complex interaction of natural frequencies of each component of the tree involved in the response. It was observed that the branches of a tree respond with a complex sway motion in which the limbs move out of step with each other to ensure that harmonic or pendulum like

motion is never achieved and energy is dissipated before it is transferred to the trunk (James 2003). It was also noted that there is great difficulty in analyzing trees with engineering equations because the simplifying assumptions upon which the equations are derived are often violated when applied to trees (Kane et al. 2009).

Kane and James (2011) documented the complex dynamic response of two species of tree using strain meters during pull and release testing. The frequency of leafless trees was found to be 2.5 times greater than the frequency of trees in leaf (Kane & James 2011). Also, they observed that trees in leaf experience greater drag and absorb more wind energy, but they dissipate energy more rapidly than leafless trees (Kane & James 2011). Sellier et al. (2006) used pull and release testing to determine frequency and damping ratio while developing a finite element model for maritime pine saplings. The model indicated that the presence of needles was responsible for around 80% of overall damping, while wood viscosity and the soil/root system were each responsible for 10% (Sellier et al. 2006). It was also concluded that stem/root anchorage stiffness parameters cannot be neglected in dynamic modeling (Sellier et al. 2006). Both studies demonstrated the large contribution that leaves make to the dynamic properties of a tree.

Finite element modeling and theoretical dynamic analysis have been used to further investigate the effect of specific morphometric parameters on the dynamic characteristics of tree structure. Sellier and Fourcaud (2009) investigated how changing various aerial morphometric and material property characteristics impacted the dynamic response of a 35 year old maritime pine (*Pinus pinaster*) using finite element modeling. Changing aerial morphology parameters including branch attachment angle, mean basal diameter of 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> order branches (axes), and the length of 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> order

branches (axes) lead to significantly larger changes in sway frequency and damping ratio than changes to material property parameters (Sellier and Fourcaud 2009). While investigating the impact of material properties parameters it was found that varying the value of branch modulus of elasticity had a direct impact on the sway frequency of the model tree and variations in the leaf area and leaf distribution of 2<sup>nd</sup> and 3<sup>rd</sup> order branches (axes) had a direct impact on the effective damping ratio of the model tree (Sellier and Fourcaud, 2009). Similar findings were reported by Moore and Maguire (2008) who observed that decreases in the value of branch modulus of elasticity lead to increased levels of damping in a finite element model of 20 year old Douglas fir (*Pseudotsuga menziesii*) trees.

Moore and Maguire (2008) also found that the dynamic response factor, a measure of response amplification due to dynamic loading regimes versus equivalent static loading and referred to as a mechanical transfer function in the text, peaked when the forcing function frequency was near or equal to the natural frequency of vibration of the entire tree. The value of the dynamic response factor was observed to decrease rapidly as the forcing function frequency increased beyond the natural frequency of vibration of the entire tree (Moore and Maguire 2008). The dynamic response factor was found to decrease more rapidly when the forcing frequency exceeded the natural frequency of the tree when the simulated load was applied to the branches as opposed to the trunk as well as when the modulus of elasticity of the branches was decreased (Moore and Maguire 2008). This finding is supported by the findings of Ciftci et al. (2013) where various components of aerial architecture were analyzed for a sugar maple (*Acer saccharum*) in a finite element model. It was found that as branches were systematically

added to the model, peaks in the dynamic response factor were increased at the resonant frequencies associated with the branches and decreased at the resonant frequencies associated with the stem and uppermost branch (Ciftci et al. 2013).

The previous studies provide support for the updated dynamic model of trees where branches are considered individual tuned mass oscillators attached to the main stem as a cantilever, as opposed to lump masses distributed along the length of the stem. This updated dynamic model allows for a damping mechanism termed mass (James et al. 2006) or multiple resonance (Spatz et al. 2007) damping where wind energy is transferred from the trunk to 1<sup>st</sup> order and larger order branches, a claim supported by Rodriguez et al. (2012) who observed that as branch order increased an increasing number of vibrational modes become concentrated in the higher order branches, allowing for increased energy dissipation from the trunk and lower order branches. A review of the previous work leading to the structural damping model is provided by Spatz and Theckes (2013).

The effect of steel support cables on the dynamic properties of large deciduous trees was not encountered in the preceding literature review. The main objective of this study is to determine the effect, if any, that steel support cables have on the dynamic properties of large deciduous trees both in and out of leaf.

## CHAPTER 3

### MATERIALS AND METHODS

#### Study Site and Sample Selection

Twelve northern red oak (*Q. rubra*) trees were selected in the Urban Forestry Research Plot located within the Cadwell Forest in Western Massachusetts (see Figure 1). The trees were selected based on common characteristics, including: diameter at breast height (DBH), total height, presence of co-dominant stems, and canopy architecture. Morphometric data for the sample trees are presented in Table 1.

Table 1. Morphologic characteristics of northern red oak (*Q. rubra*) trees used for free vibration testing. Mean values with standard error in brackets.

	N	DBH (cm)	Height (m)	Height to Union (m)	Cable Span (m)	Cable Tension: Leaf On (N)
<b>Cable</b>	6	43.9 [4.76]	21.9 [2.75]	10.4 [1.67]	2.7 [1.21]	49.9 [18.06]
<b>No Cable</b>	6	42.7 [3.89]	20.4 [2.61]	13.2 [3.14]	1.2 [0.21]	~~~~~

Six of the twelve trees were randomly selected to have steel support cables installed between their co-dominant stems in accordance with the ANSI A300 Standard for Tree, Shrub, and Other Woody Plant Maintenance: Supplemental Support Systems (Anonymous, 2006). The static support system consists of a 7-strand high strength steel cable installed between the co-dominant stems approximately two-thirds of the vertical distance between the co-dominant union and the top of the shorter stem.

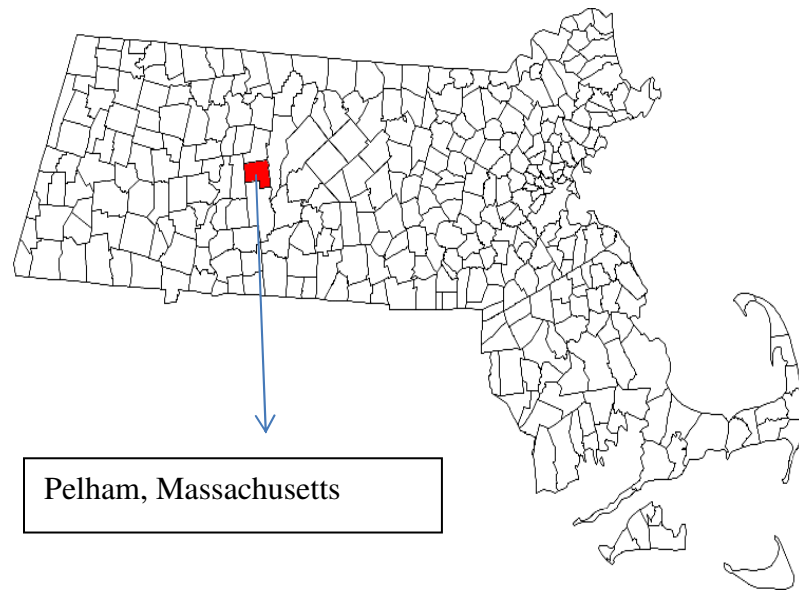


Figure 1. The Cadwell Forest Urban Forestry Research Plot is located in western Massachusetts within the town of Pelham, in Hampshire County.

A dead-end system was installed which required drilling a hole through each stem which the cable was then passed through and terminated with a dead-end cable stop (RigGuy Inc., Athens, Ga, USA). No eye-bolts or preformed splices were used in the steel cabling assembly. The six trees that did not have static support cables installed had one hole drilled in each of the co-dominant stems at the height that a cable would have been installed in order to limit uncertainty associated with the biomechanical effect of the holes on the dynamic response of the tree to free vibration testing.

### **Free Vibration Testing**

The free vibration testing was accomplished by pulling the trees to an initial displacement and then releasing them to oscillate back to an at rest position. The acceleration experienced by the trunk was recorded by an accelerometer (Microstrain, G-Link 2g, +/- 10 mg) for approximately 30 s after the release of the tree. The accelerometer was attached to the trunk at the co-dominant union (+/- 30.5 cm [12 in])



along with a base station which was connected to a laptop with a 60 foot cord composed of 4 live USB 2.0 cables (Gigaware, RadioShack) that are 4.57 m (15 ft) long connected end to end. The rope used to pull the tree was also attached to the stem at the co-dominant union. A plumb bob attached at the co-dominant union measured initial displacement of the trees before they were released (see Figure 2). This displacement, along with the measured tension in the pull rope, was then used to calculate the effective stiffness of the tree and root-plate as a whole. The trees were pulled and released 3 times in the incident direction and 3 times in the orthogonal direction with respect to the support cable between the co-dominant stems.



Figure 2. Hardware installation in sample tree. The accelerometer is mounted at the co-dominant union along with the base station and plumb-bob. The pull rope is attached to the stem directly below the plumb-bob in order to avoid interference during testing.

The accelerometer is a Microstrain G-Link tri-axial accelerometer with a range of  $\pm 2g$ , accuracy of 10 mg, and resolution of 1.5 mg. The accelerometer is rigidly mounted on a 12.7 cm (5 in) square by .95 cm ( $\frac{3}{8}$  in) thick hard plastic plate for ease of installation. The base station is a Microstrain 2.4 GHz USB 2.0 base station used to communicate with the accelerometer and data logging software. The base station is

mounted on a 8.9 cm (3.5 in) by 16.5 cm (6.5 in) by 2.5 cm (1 in) thick wooden base for ease of installation. The accelerometer and base station were secured to the tree using 7.2 cm (3 in) self-drilling coarse thread exterior wood screws so that they were tight against the tree trunk and unable to move freely.

The software used to communicate with the accelerometer is Microstrain Node Commander version 1.5.26. The software was used to configure the accelerometer to perform 1000 sweeps at 32 Hz for a sampling period of 31.25 seconds. The accelerometer recorded the experienced acceleration during each sweep and the corresponding time. This data was automatically saved in the memory of the accelerometer. The data were then downloaded onto a Panasonic CF-52 laptop with a Microsoft Windows XP 2002 operating system using the Microstrain software. The data were viewed in Microsoft Office Excel 2003 and saved as a comma delimited (.csv) file. Data were then copied and saved as a Microsoft Excel 97-2003 Worksheet (.xls) to be used with the analysis software. The physical memory on the accelerometer was then erased to prevent more than one trigger being stored on the accelerometer at any time and prevent accidental duplication. This process was performed between each pull and release of the sample tree, yielding six separate comma delimited files with corresponding worksheets. Each pair corresponded to a single pull and release of the tree. The direction of pull, incident or orthogonal, was recorded in the file name.

The sample tree was then pulled and released according to the following method. An arborist block with a 2-ton working load limit (WLL) was attached at the base of another tree in either the incident or orthogonal direction from the sample tree to serve as a re-direct for the rope used to tension the pull line. A 2.5 cm (1 in) by 4.9 m (16 ft)

Tenex Loopie sling was used to attach the block to the base of the tree. On a nearby tree, a Good Rigging Control System (GRCS) device was mounted upside down at chest height. An arborist block with a 1818 kg (2 ton) WLL was attached at the base of the tree to re-direct the tension rope into the GRCS. A 1.9 cm ( $\frac{3}{4}$  in) by 2.4 m (8 ft) long Samson Stable Braid sling was used to attach the block. Directly above the arborist block a 2.5 cm (1 in) by 2.4 m (8 ft) Tenex sling was attached to the tree as an anchor point for a Dillon EdXtreme dynamometer (4545 kg capacity accurate to 0.91 kg; Weigh-Tronix, Fairmont, MN). A 6363 kg (7 ton) WLL galvanized steel shackle was used to attach the dynamometer to the Tenex sling. A 681 kg ( $\frac{3}{4}$  ton) continuous rope puller was attached to the free end of the load cell using a 4090 kg (4.5 ton) breaking strength SMC Extra-Large Steel 'D' carabiner (see Figure 3).

After the hardware was installed, a length of arborist climbing line was threaded through both blocks and attached to the pull line to serve as the tensioning line. A figure eight loop was used to attach the climbing line to a bowline on a bite tied in the pull line with a 5114 kg (11,250 lb) breaking strength steel HMS carabiner (see Figure 4). The continuous rope puller was then attached to the climbing line using a mid-line 23ehavio and pulley to create a 2:1 mechanical advantage. The GRCS and rope puller were then used to tension the climbing line between 681-909 kg (1,500-2,000 lbs). The climbing line was then removed from the GRCS and the tension recorded from the load cell. The displacement of the tree was also recorded at this time using the plumb-bob mounted on the sample tree. The accelerometer was then triggered and the climbing line cut with a hand saw directly behind the 2-ton arborist block used as a re-direct. The accelerometer measured the acceleration time history as the tree oscillated back to an at rest position.

In order to determine the effect that leaves had on the dynamic response the trees were subjected to free vibration testing with and without leaves present. This was accomplished by testing the trees during an interval in the dormant season (March of 2012) and an interval in the growing season (September of 2012). This allowed for the effect of leaves to be isolated and the remaining effect of the steel support system to be identified.



Figure 3. The hardware configuration for pulling and releasing the sample trees. The rope puller is attached to the white tensioning line with a mid-line 24ehavio and pulley outside the scope of the picture. The white tensioning line is re-directed through an arborist block on an adjacent tree.

The frequency of oscillation for each tree was determined by calculating a Power Spectral Density (PSD) for the acceleration time series. The PSD analysis was performed in MATLAB (Mathworks R2010a) using the Welch method. The damping ratio ( $\zeta$ ) was



calculated in MATLAB by fitting a decaying exponential function to the peaks in the acceleration time history of each trial pull and release. The decaying exponential had the form;

$$\rho e^{-\zeta \omega_n t}$$

. The damping ratio was determined by dividing the exponent value of the fitted curve by the frequency determined by the PSD analysis for each pull and release test, resulting in 6 values of damping ratio per tree per leaf condition.



Figure 4. The attachment of the tensioning rope to the pull rope. The tensioning rope was re-directed through the arborist block and attached to the pull rope in the manner above. The tensioning rope was then cut with a handsaw directly before the arborist block allowing the tree to oscillate back to an at rest position.

Linear mixed effects models were fit in R (Version R64 2.15.2, CRAN Mirror USA:Md, 10/2012) for frequency and damping ratio. Cable, leaf, and direction of pull were categorical predictors in each model. A categorical variable with 12 levels (A-L), one level for each sample tree, was entered as a random effect in the model to account for between subject variability. The random effect was nested within the cable predictor. The models were fit using the ‘lmer’ function within the ‘lme4’ package (CRAN Mirror

USA:Md, 12/2012). An analysis of variance was performed to determine the significance of each predictor in the models. Additionally, multiple regression was performed in order to determine the relationship, if any, between DBH, total tree height, height to the co-dominant union, and the ratio of DBH over total tree height squared and frequency and damping ratio.

## CHAPTER 4

### RESULTS

It was not possible to determine  $f_n$  and  $\zeta$  from the time histories of two trees (one with a cable and one without) because adequate excitation was not achieved. The trees had an average DBH of 47.5 cm and an average height to the co-dominant union of 8.6 m. The tensions achieved in the pull rope as outlined in the methods section were not large enough to achieve an adequate acceleration time history needed for the PSD analysis. As a result these two trees were not included in the mixed effects models. This left  $n=5$  trees in both the cable and no-cable treatments of the model (Table 2).

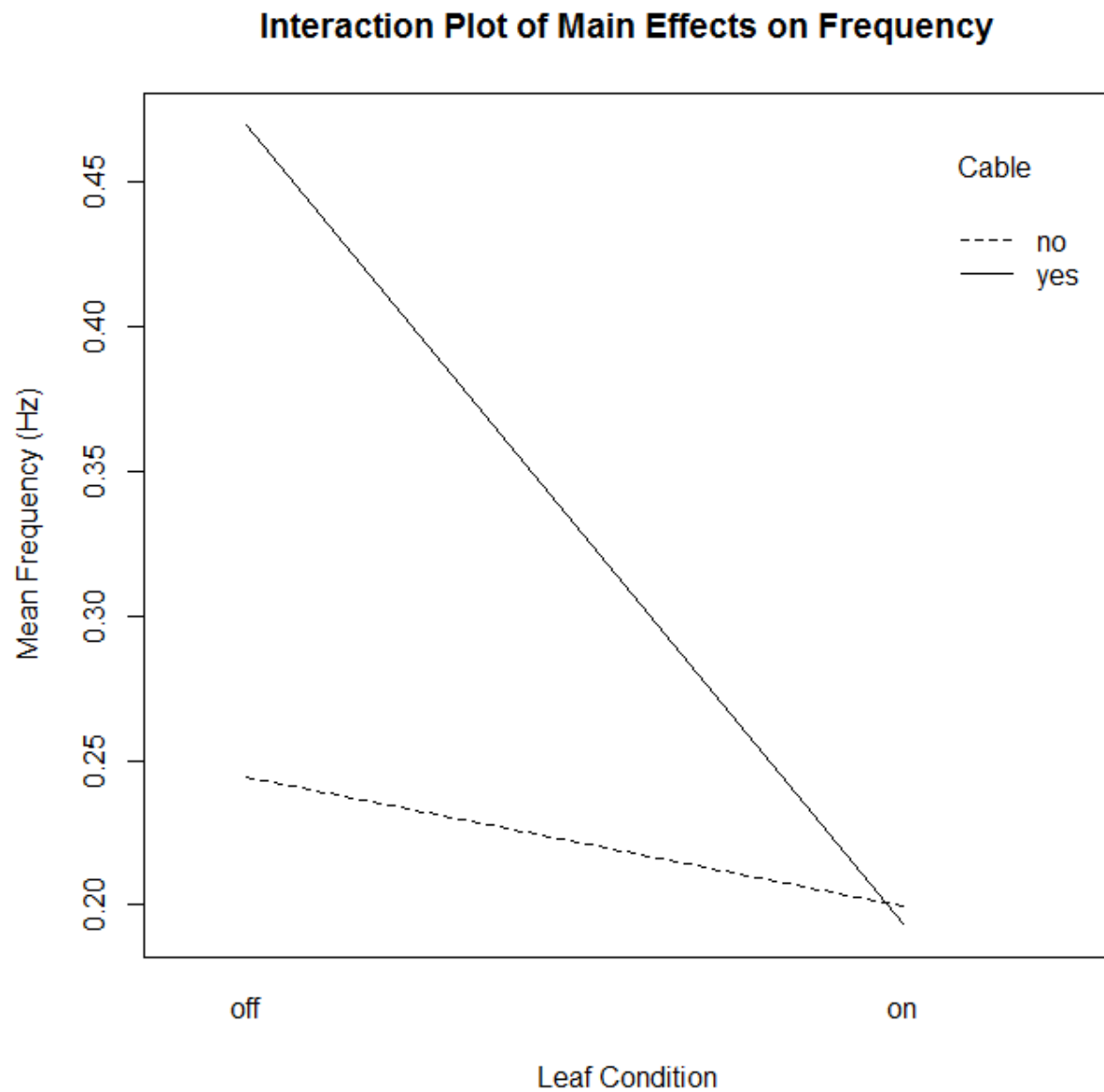
Table 2. Morphologic characteristics of northern red oak (*Q rubra*) trees used for free vibration testing after removing the two inadequately excited trees. Mean values with standard error in brackets.

	N	DBH (cm)	Height (m)	Height to Union (m)	Cable Span (m)	Cable Tension: Leaf On (N)	Stiffness (EI): Leaf Off ( $N \cdot m^2$ )
<b>Cable</b>	5	42.9 [4.46]	21.9 [3.07]	11.0 [1.19]	2.9 [1.27]	49.3 [20.01]	8.68E6 [3.29E6]
<b>No Cable</b>	5	42.1 [4.02]	20.9 [2.59]	13.9 [2.81]	1.1 [0.09]	~~~~~	9.64E6 [7.9E6]

### Frequency

Frequency was greater on trees with cables and when trees were leafless. The direction of initial displacement did not affect frequency. The interaction between the cable and leaf main effects was significant (See Table 3). The effect of the cabling treatment on frequency was greater in the leaf off condition than the leaf on condition (See Figure 5).





**Figure 5:** Interaction plot of frequency by cable treatment and leaf condition. The difference in mean frequency between cabled trees and non-cabled trees is larger in the leaf off condition.

Table 3. ANOVA table for mixed effects model of (a) frequency and (b) damping ratio.

Effect	Level	Df	F-Value	p-value	Mean (STDERR)
(a) Cable		1,8	5.27	0.051	

	Yes			.331(.208)
	No			.222(.035)
<b>Direction</b>		1,8	2.79	0.133
	Incident			
	Orthogonal			
<b>Leaf</b>		1,8	16.03	0.004
	On			.196(.028)
	Off			.357(.191)
<b>Cable*Direction</b>		1,8	2.86	0.129
<b>Cable*Leaf</b>		1,8	8.39	0.019
<b>Leaf*Direction</b>		1,8	3.41	0.102
<b>Cable*Direction*Leaf</b>		1,8	3.27	0.108
<b>(b) Cable</b>		1,8	.919	0.366
	Yes			
	No			
<b>Direction</b>		1,8	2.59	0.146
	Incident			
	Orthogonal			
<b>Leaf</b>		1,8	31.66	<0.001
	On			.121(.066)
	Off			.046(.030)
<b>Cable*Direction</b>		1,8	0.04	0.852
<b>Cable*Leaf</b>		1,8	1.98	0.197
<b>Leaf*Direction</b>		1,8	0.61	0.457
<b>Cable*Direction*Leaf</b>		1,8	0.22	0.652

### **Damping Ratio**

Damping ratio was greater when trees were in leaf (Figure 6), but no other effects in the model, nor their interactions, affected damping ratio (Table 3).

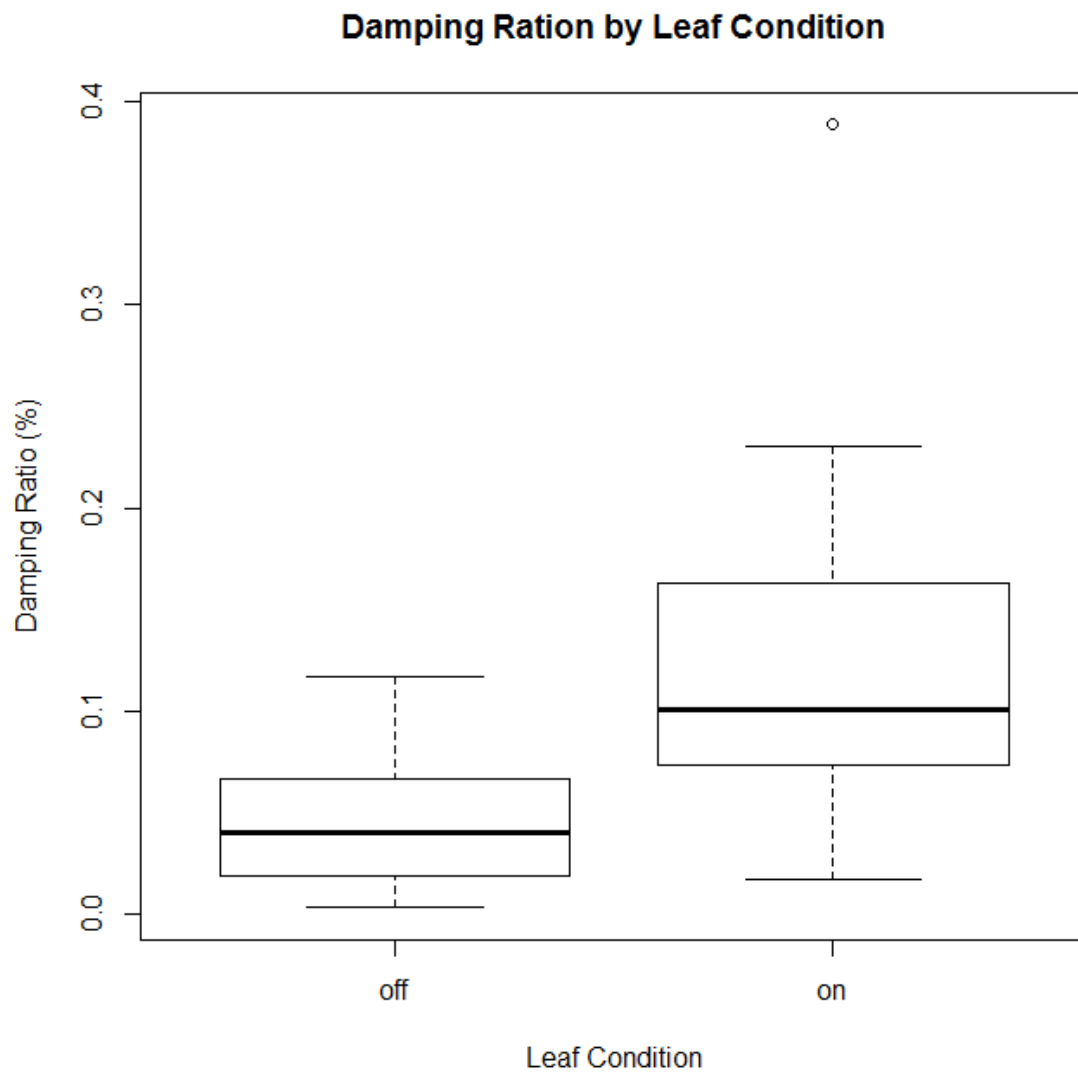


Figure 6. Box plot of damping ratio by leaf condition.

## CHAPTER 5

### DISCUSSION

This study contributes to a small but growing body of knowledge on the dynamic properties of mature deciduous trees. It provides valuable methods and data for trees with and without leaves as well as with and without steel support cables. Previous studies have employed similar methods determining natural frequency and damping ratio from displacement time history during free vibration testing (Sellier et al. 2005), velocity time history during wind induced swaying (Baker 1997), and strain time history during free vibration testing (Kane & James 2011). Our study employed the acceleration time history during free vibration testing and is related as the second derivative of the position time history and first derivative of the velocity time history.

The frequency values determined during the study ranged from approximately .18 Hz to 1.2 Hz across all treatments and sample trees (see **Error! Reference source not found.**Figure 5). Milne (1991) observed natural sway frequencies between .24-.4 Hz for Sitka spruce (*Picea sitchensis*) grown in a traditional plantation setting in Scotland. Roodbaraky et al. (1994) observed values between .42-.80 Hz in pull and release (free vibration) testing that spanned two years and included leaf on and leaf off conditions of a single plane tree (*Platanus sp.*) on the campus of the university of Nottingham. The observed values are similar to those observed by Baker (1997) for diseased and healthy lime (*Tilia x Europaea*) trees that ranged from approximately .6 Hz to 1.4 Hz and .2 Hz to 1.4 Hz, respectively, across sample tree and leaf condition. Moore and Maguire (2005) observed natural sway frequencies between 0.4-0.7 Hz for 9 Douglas fir (*Pseudotsuga menziessii*) grown in a plantation setting when contact with neighboring trees was

removed. The observed values from this study are similar to those observed by Sellier et al. (2006) for complete maritime pine (*Pinus pinaster*) saplings that ranged from approximately .6 Hz to .8 Hz as well as those observed by Jonsson et al. (2007) who observed values between .17-.29 Hz for Norway spruce (*Picea abies*) growing on subalpine, forested slopes. Kane and James (2011) observed values ranging from approximately .4 Hz to 1.2 Hz across pruning treatments of chestnut oak (*Quercus prinus*) and .4 Hz to 1 Hz across pruning treatments and leaf condition of Bradford pears (*Pyrus calleryana*).

The damping ratios observed in this study ranged from approximately 2%-12% across all sample trees and treatments (Figure 6). Milne (1991) observed damping ratios between 10%-22%, however, these values were reduced to between 5%-8% when contact with neighboring trees was eliminated during sway testing. Roodbaraky et al. (1994) observed damping ratios between 4%-6% for a single tree during multiple tests spanning 2 years. Moore and Maguire (2005) observed damping ratios between 5%-24% during free vibration testing of 9 Douglas fir trees when contact with neighboring trees was removed. Sellier and Fourcaud (2006) observed damping ratios between 6%-9% for maritime pine saplings using similar methods. Jonsson (2007) observed values for damping ratio between 3%-10% for Norway spruce on subalpine forested slopes. Kane and James (2011) observed damping ratios between 4%-7% for Bradford pears and 5%-10% for chestnut oaks, however, direction of pull was found to have a significant effect on the value of damping ratio in their study.

Frequencies of cabled trees were higher than frequencies of non-cabled trees regardless of leaf condition (see **Error! Reference source not found.**Figure 5). It

should be noted that the effect of the cable is much greater in the leaf off condition than the leaf on condition. This is similar to the finding of Kane & James (2011) that the effect of pruning was not as great as the effect of leaf condition on the frequency of Bradford pears.

The leaf condition had a significant impact on the natural frequency of the study trees. Frequencies of trees in the leaf off condition were larger than trees in the leaf on condition regardless of cabling treatment (Figure 7). Additionally, leaves had a significant effect on the damping ratio of the sample trees. Trees in the leaf on condition had larger damping ratios than trees in the leaf off condition (Figure 6).

The trees used in this study were larger in either mean height or mean diameter, or both, than those used in studies by Milne (1991), Baker (1997), Moore and Maguire (2005), Kane et al. (2011), and Sellier et al. (2006) (see Table 4). Sellier et al. (2006) used three plantation grown maritime pine saplings that were not included in the table. Baker (1997) and Kane & James (2011) measured open grown deciduous trees on or around college campuses. The trees in this study were located in an interior forest stand. Open grown trees tend to have larger diameter trunks and shorter heights compared to similar aged trees in forest stands because the physical environment and biomechanical constraints determine the growth and resulting form of trees (James et al. 2006). Forest grown trees are offered protection from wind, snow, and ice loading by the surrounding trees and do not develop trunks and root plates as rigid as open grown trees (Niklas 1993). Values of root plate and trunk stiffness were not determined in this study which is one limitation of the experimental design.

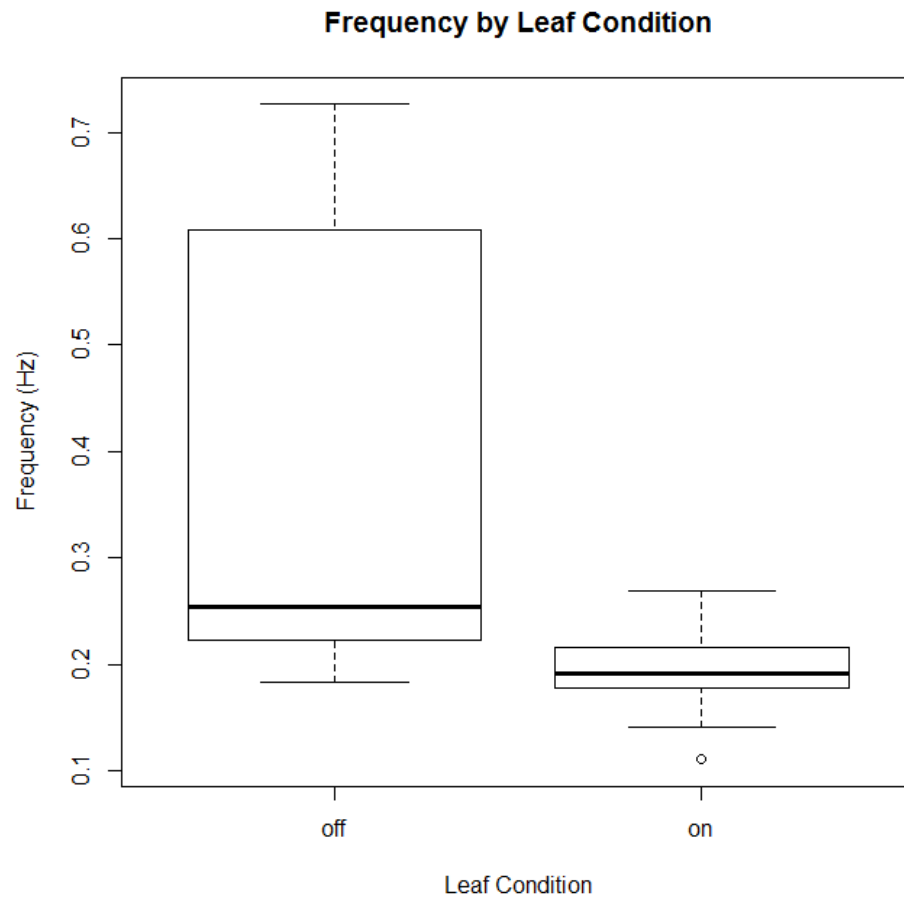


Figure 7. Frequency by leaf condition.

Table 4. Morphologic measurements of sample trees used by Milne, Baker, Kane and James, and this study. Mean values with standard errors in parentheses.

	<b>DBH (cm)</b>	<b>Height (m)</b>
Milne	14.5 (3.02)	14.2 (0.90)
Baker	50.7 (17.39)	13.1 (3.37)
Moore and Maguire	28.9 (7.34)	16.8 (2.09)
Kane & James (Bradford pear)	19.9 (2.9)	7.87 (0.48)

Kane & James (chestnut oak)	6.9 (1.0)	5.16 (0.63)
Measured	43.35 (4.20)	21.2 (2.67)

Both cable condition and leaf condition had a significant effect on the sway frequency of the sample trees (Table 3). This is in agreement with both theoretical physical analyses and previous studies. Regarding cabling condition, the presence of a cable was attributed with an increase in the equivalent stiffness of canopy components with no change in mass versus the no cable treatment, resulting in an increase in frequency. Moore and Maguire (2008) found that natural frequency was highly sensitive to branch modulus of elasticity in a finite element model of 3 Douglas fir trees. Sellier and Fourcaud (2009) found that modulus of elasticity was the only material property that effected the natural sway frequency in their finite element model. Changes in aerial morphology were found to have greater effects on natural sway frequency than changes to constituent material properties (Sellier and Fourcaud 2009). The installation of the steel support cable in the sample trees of this study did not change the aerial morphology of the canopies (eg: branch angle, branch length, branch orientation, slenderness ratio, leaf area, leaf linear density), indicating the increased stiffness associated with cable installation is representative of an increase in modulus of elasticity for the cabled elements.

Changes in branch modulus of elasticity have also been demonstrated to affect damping ratio and stress dissipation in finite element modeling. Moore and Maguire (2008) found that as the modulus of elasticity of branch components decreased, the damping ratio of the model tree increased. Cabling was not found to have an effect on



the damping ratio of the sample trees (Table 3). This is likely due to the equivalent increase in modulus of elasticity being localized to the two primary branches between the cabling location and co-dominant union. The second and higher order branches attached to the cabled primary branches are still free to oscillate as the second and higher order branches of the non-cabled trees. This indicates that the stem and primary branches play a less significant role in damping than the second and higher order branches. This has been previously demonstrated by Sellier and Fourcaud (2009) who found that in addition to changes in aerial morphology; changes in wood viscosity, specific leaf area, and leaf linear density of 2<sup>nd</sup> and 3<sup>rd</sup> order branches resulted in changes to the damping ratio of the tree. Additionally, Rodriguez et al. (2012) observed that increases in branch order were associated with increases in modal frequency concentration. The concept of multiple resonance damping (Spatz et al. 2007) is based on overlap between the frequency bands of the stem, primary, secondary, and higher order branches so that energy can be dissipated over the entire tree (Moore and Maguire 2008). The result is energy being transferred from the stem to higher order branches where it is most effectively dissipated in the periphery of the tree (Spatz and Theckes 2013). This indicates that the localized increase in stiffness of the cabled primary branches did not interrupt the transfer of energy through overlapping frequency bands and did not have any resulting effect on the overall damping ratio.

Leaf condition was also found to have a significant effect on the frequency of vibration of the sample trees, with trees in the leaf on condition having significantly smaller frequencies than trees in the leaf off condition (Table 3). The effect of leaves on

the frequency of vibration is also in agreement with theoretical analyses and the results of previous studies. The circular frequency is defined as (Chopra 2007)

$$\omega_n = \sqrt{\frac{k}{m}}$$

where  $k$  is the equivalent stiffness and  $m$  is the total mass. The presence of leaves in the canopy increases the mass of the overall system when compared to periods when leaves are not present, resulting in a smaller frequency value. Roodbaracky et al. (1994) found that stiffness did not vary by season while performing pull and release testing on a range of deciduous street trees, and trees in the leaf on condition had a significantly lower frequency than trees in the leaf off condition. Baker (1997) and Kane and James (2011) reported similar findings that trees in the leaf on condition had significantly lower frequencies than trees in the leaf off condition. The presence of leaves in the canopy also causes an increase in aerodynamic drag that serves to lower the frequency of deciduous trees in the leaf on condition. Also, the significant interaction of the leaf condition and cable treatment main effects indicates that the change in mass caused by the presence of leaves is more significant than the increased stiffness associated with the steel cable (Error! Reference source not found.Figure 5), a finding similar to that of Kane and James (2011) where the effect of pruning on frequency was small in comparison to the effect that leaves had on the frequency of sample trees.

Leaves also had a significant effect on the damping ratio of the sample trees, with trees in the leaf on condition having significantly larger damping ratios than trees in the leaf off condition. No other effects, nor their interactions, were found to be significant (Table 3). This is in agreement with previous studies like Roodbaracky et al. (1994),

Baker (1997), and Kane and James (2011) who reported similar findings that the damping ratios of trees in the leaf on condition were significantly larger than the leaf off condition. Sellier et al. (2006) found that needles were responsible for approximately 80% of overall damping in a finite element model of maritime pine saplings, a follow up to the free vibration testing undertaken in 2005 where foliage was determined to be the source of damping in the saplings (Sellier and Fourcaud 2005). The result is also in agreement with the theoretical framework of multiple resonance damping outlined in Spatz et al. (2007).

Multiple resonance damping describes the transfer of motion energy from the stem to the primary and higher order branches through overlapping regions of their respective frequency bands (Spatz et al. 2007, Rodriguez et al. 2012, Spatz and Theckes 2013). Spatz et al. (2007) found that primary branches of Douglas fir trees sampled longer than 0.5 m had similar frequencies to the main trunk allowing for multiple resonance damping. Additionally, it was determined that the total measured damping of the sample trees was greater than the sum of aerodynamic and viscous damping, indicating that multiple resonance damping was occurring (Spatz et al. 2007). Rodriguez et al. (2012) demonstrated that as branch order increased, the number of modal frequencies concentrated in the higher branching orders increased, allowing for motion energy to be dissipated over several modes. Ciftci et al. (2013) demonstrated this as well by showing that as branches of similar natural frequencies were added to a sugar maple (*Acer saccharum*) in a finite element model, local maxima in the dynamic response factor were decreased in the frequency range corresponding to the stem and increased in the frequency range corresponding to branches.

In the framework of multiple resonance damping, leaves serve to add mass to the higher order branches and lower their frequencies causing greater overlap with the frequencies of lower order branches and the stem (Figure 8). The increased overlap in the frequency bands would cause more energy to be dissipated in the frequency modes concentrated in the higher order branches. This was evidenced in this study by the appearance of multiple, smaller peaks in the PSD plots for the same tree between the leaf off (Figure 9) and leaf on tests (Figure 10).

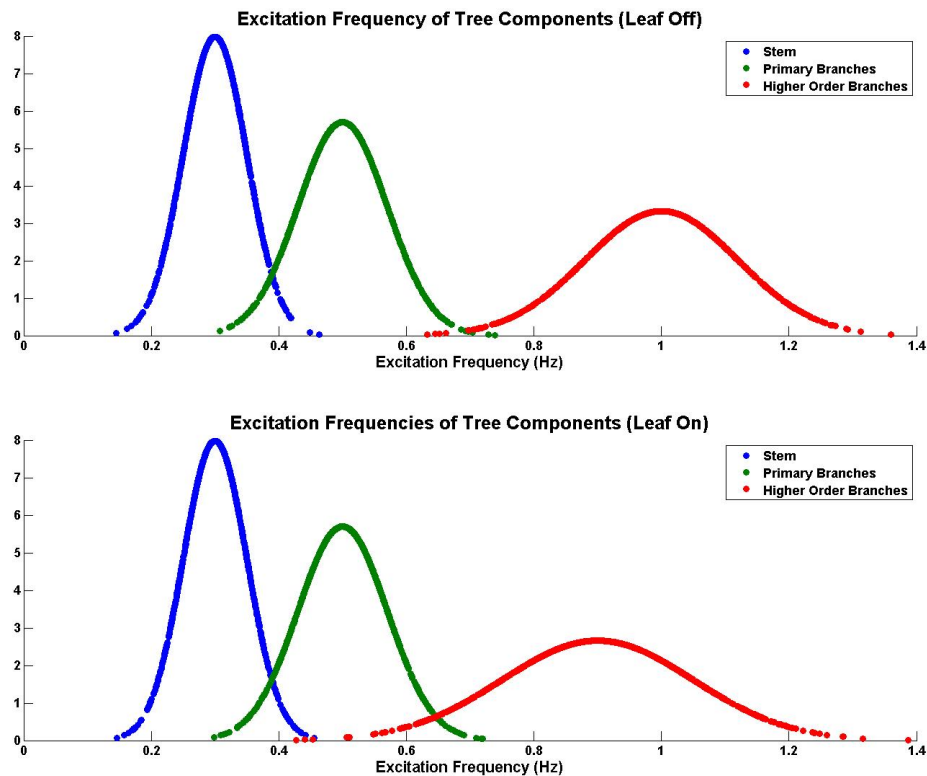


Figure 8. Simulated frequency distributions for tree components. The increased overlap of the second and higher order branch frequency band (red) with the primary and stem frequency bands (green and blue, respectively) by leaf condition. Leaf Off (top) and Leaf On (bottom).

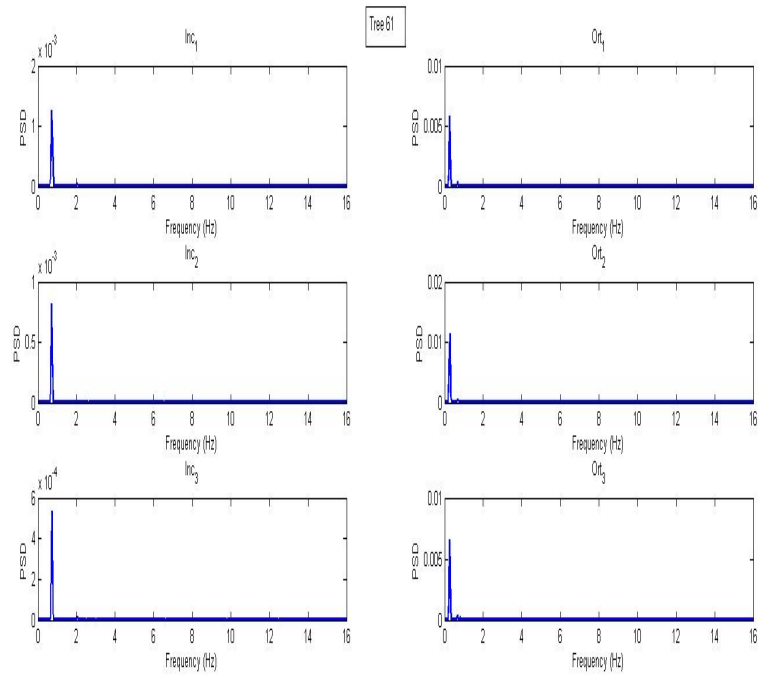


Figure 9. PSD plots for sample tree in Leaf Off condition.

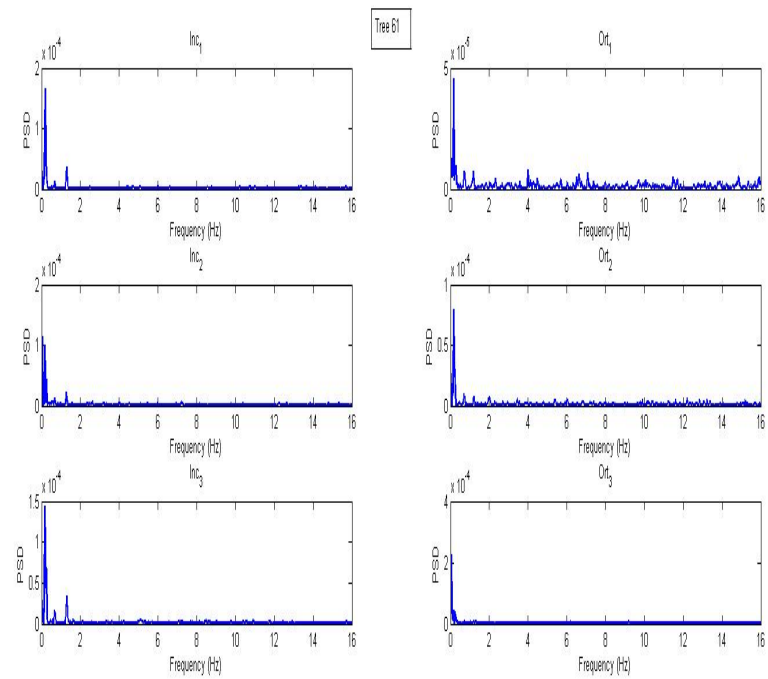


Figure 10. PSD plots for sample tree in Leaf On condition.

The presence of multiple, smaller peaks in the PSD plots of the sample tree in the leaf on condition indicate that higher order modes of vibration were being excited during the pull and release testing. Moore and Maguire (2008) found that when a simulated load was applied to the trunk of the tree in their finite element model, the dynamic response factor decreased less rapidly once the forcing frequency surpassed the natural sway frequency than when the simulated load was applied to the branches. This indicates that wind energy is largely dissipated in the periphery of the crown before it can be transmitted to the primary limbs and stems (Moore and Maguire 2008, Spatz and Theckes 2013). In this study, the load was applied directly to the stem and transferred out to the primary and higher order limbs. The PSD plots (Figure 9 & Figure 10) indicate that the higher order limbs played a more significant role in the leaf on condition and are responsible for the increase in damping ratio between the leaf off and leaf on conditions, as expected from the framework of multiple resonance damping.

These results indicate that second and higher order branches as well as leaves play a significant role in the ability of a tree to withstand dynamic loading regimes. Hazard tree assessment, in particular, is concerned with determining the likelihood of tree failure during both routine and extreme weather events, and cabling is often employed as an arboricultural tool to reduce the likelihood of failure.

This study did not find any effect of cabling on the damping ratio of the sample trees, however, one limitation of the experimental design is that pruning treatments were not administered in conjunction with cable installation; a common practice by field arborists. Kane and James (2011) found that pruning treatments (reduction and thinning) had a similar effect of increasing the frequency of leafless Bradford pear trees, however,

in the leaf on condition, reduction pruning increased the frequency of sample trees while thinning was not shown to have an effect on frequency statistically different from '0'. Cabling was not a treatment in their study. With the absence of empirical evidence on the effects of pruning and cabling together, caution should be taken during cabling operations for the following reason.

The installation of a steel support cable was shown to increase the frequency of sample trees ( $\overline{f_{n,no\ cable}} = .222\ Hz$ ,  $\overline{f_{n,cable}} = .331\ Hz$ , see Table 3) in this study. Reduction pruning is often administered in conjunction with cable installation in order to reduce the moment arm or leverage acting on the suspect union, and has been shown to increase the frequencies of pruned trees in both the leaf off and leaf on conditions (Kane and James 2011). The increase in frequency caused by the cable is localized on the primary branches that the cable is attached to, leaving higher order limbs free to oscillate as in non-cabled trees. The increase in frequency caused by properly administered reduction pruning would likely affect primary and higher order limbs as the goal of the pruning is to reduce the canopy on all sides. It is worthy of future inquiry to determine if the combined effects of cabling and pruning would affect both frequency as well as damping, as the combined effects may interrupt the transfer of motion energy throughout the tree by overlapping frequency bands (Figure 8), a characteristic necessary for multiple resonance damping to occur (Spatz et al. 2007).

The results of this study indicate that cabling operations performed in accordance with the ANSI A300 (Anonymous 2006) standard and not accompanied by pruning treatments do not have an effect on the trees ability to dissipate motion energy. The increase in frequency associated with the installation of steel support cables makes the

tree susceptible to dynamic loading at a higher frequency as evidenced by the shift in the plot of dynamic response factor for cabled versus non-cabled trees (Figure 11), but does not alter the ability of the tree to dissipate that motion energy. Leaf condition not only affected the frequency of sample trees but also the ability of the trees to dissipate motion energy, as evidenced by not only the shift in the plot of dynamic response factor by leaf condition, but also the decreased amplitude of the peak value of the dynamic response factor for trees in the leaf on condition versus the leaf off condition (Figure 12).

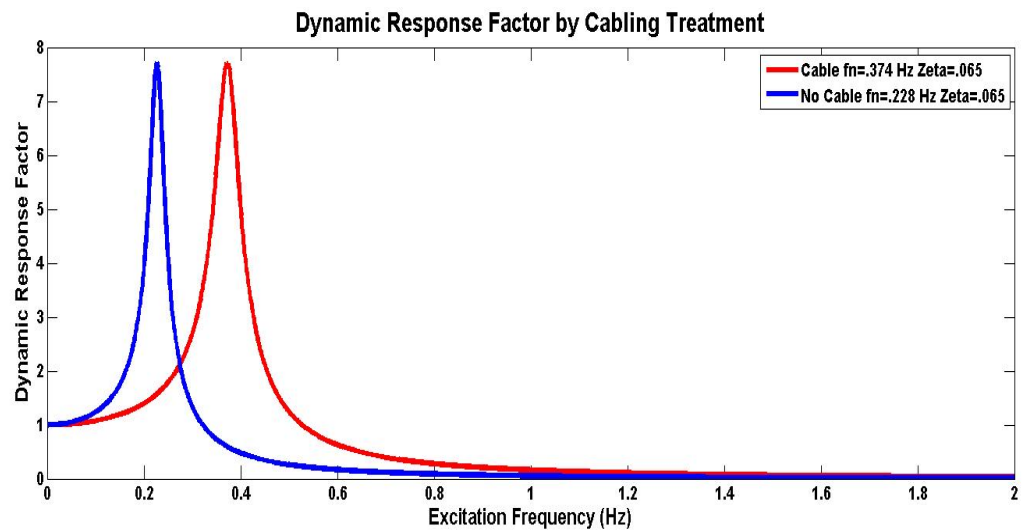


Figure 11. Dynamic response factor for cabled (red) versus non-cabled (blue) trees.

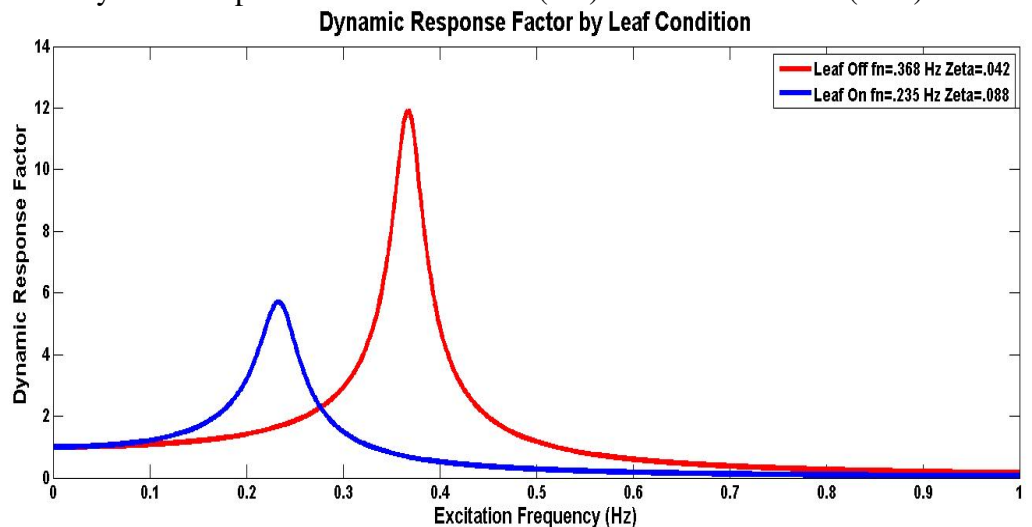


Figure 12. Dynamic response factor for trees in the leaf off condition (red) and leaf on condition (blue).



No model was found for reliably predicting natural frequency from the ratio of DBH divided by tree height squared. For non-cabled trees significant intercept terms were returned with values of .215 Hz and .175 Hz for the leaf off and leaf on condition, respectively. Previous predictive models for frequency based on DBH divided by tree height squared including Moore and Maguire's (2004) model for assorted conifers, Jonsson et al.'s (2007) model for Norway spruce, Kane and James' (2011) models for unpruned chestnut oak, raised chestnut oak, reduced chestnut oak, and pruned leafless Bradford pears over predicted the intercept values when the average value of DBH over tree height squared from our sample trees was used. Kane and James' (2011) equation for pruned in leaf Bradford pears reasonably predicted the intercept values with 4% and 17% error for the leaf off and leaf on conditions, respectively.

The DBH over tree height squared values observed in this study ranged from .06 to .13. Moore and Maguire's (2004) model for assorted conifers was based on a DBH over tree height squared range of .05 to .35, while Kane and James (2011) models for chestnut oak and Bradford pear were based on DBH over tree height squared values ranging from approximately .15 to .55. The small range of observed values from our sample trees may be one reason why a reliable predictive model for frequency based on DBH over tree height squared was not found.

The trees in this study exhibited complex canopy architecture when compared to conifers and smaller, single stem deciduous trees. The relationship between frequency and DBH over tree height squared, derived from dynamic beam theory, is predicted to be less reliable as canopy architecture deviates from a single stem with small, subordinate

branches (Sellier and Fourcaud 2009). This was observed by Kane and James (2011) who found a curvilinear relationship between frequency and DBH over tree height squared for Bradford trees, many of which had multiple co-dominant leaders originating low on the trunk.

Multiple regression analysis was performed after a reliable predictive model for frequency was not found relying on DBH over tree height squared alone. Reliable predictive models were found for the Leaf Off No Cable, Leaf On No Cable, and Leaf Off Cable groups of frequencies from the study (Figure 13). The addition of morphologic characteristics (DBH, tree height (Height), and height to co-dominant union (HeightCD)) allowed for more variation in the observed frequencies to be explained versus relying on DBH over tree height squared alone.

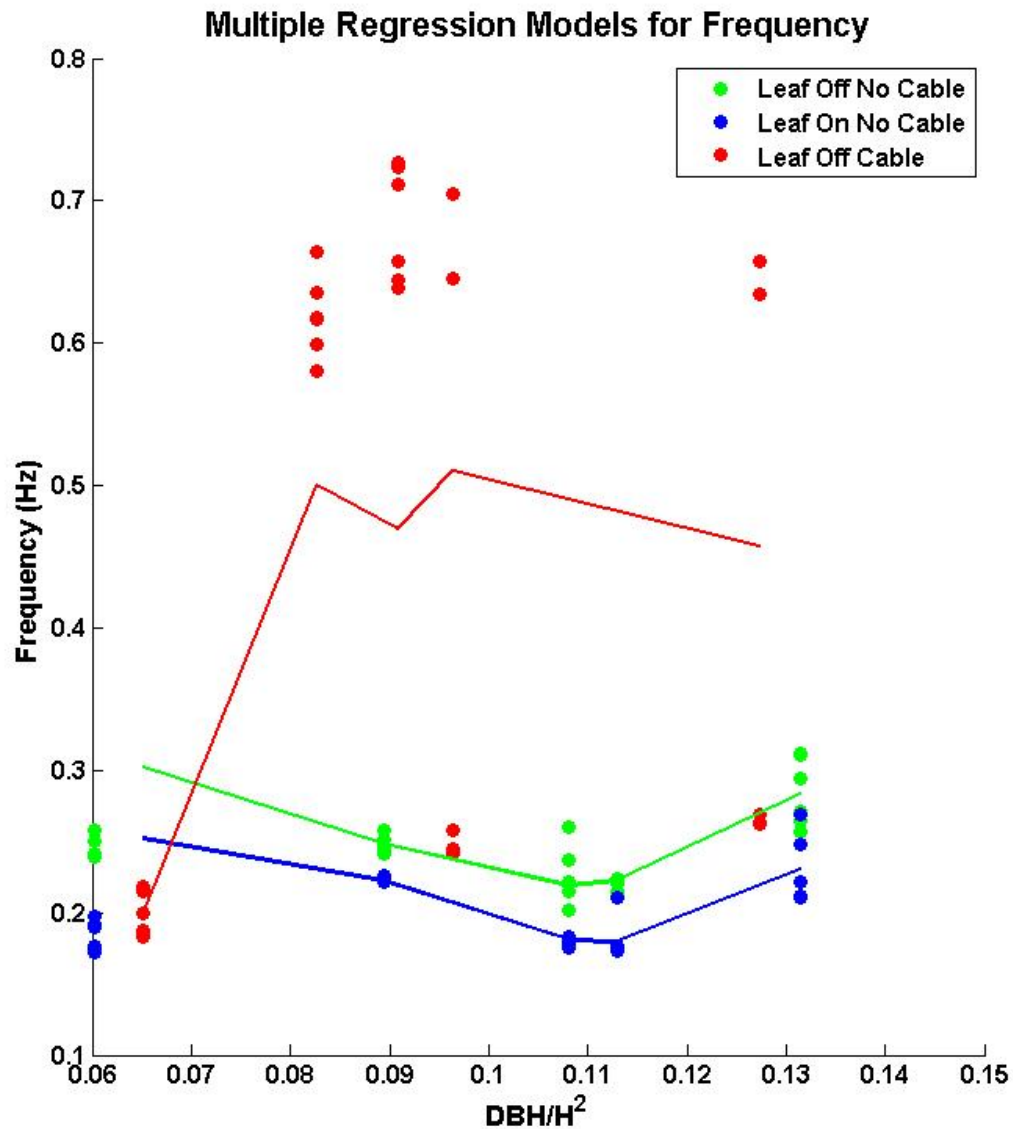


Figure 13. Scatter plot and best fit lines for the Leaf Off: No Cable (green), Leaf On: No Cable (blue) and Leaf Off: Cable (red) frequency groups. For Leaf Off : No Cable (green)  $F_n = -1.8033560 + 8.750720(DBH/H^2) - 0.011874(DBH) + 0.079818(Height)$   $\{R^2=.7284, \text{Adjusted } R^2=.697\}$ . For Leaf On:No Cable (blue)  $F_n = -1.463281 + 6.30922(DBH/H^2) - 0.005008(DBH) + 0.059322(Height)$   $\{R^2=.7741 \text{ Adjusted } R^2=.748\}$  For Leaf Off : Cable (red)  $F_n = 70.59945 - 325.9559(DBH/H^2) + 1.6801(DBH) - 2.86955(Height) + 1.43631(HeightCD)$   $\{R^2=.6485, \text{Adjusted } R^2=.5922\}$ . Only significant ( $p < 0.05$ ) model terms and coefficients listed.

No reliable predictive model was found for damping ratio from DBH over tree height squared, DBH, tree height, and height to the co-dominant union. Jonsson et al.

(2007) also failed to find a significant relationship between damping ratio and DBH, tree height, crown base, and crown length. This is likely because of the complex mechanisms by which trees dissipate dynamic stress. It is to be expected that the complex combination of viscous, aerodynamic, and multiple resonance damping can not be accounted for in traditional morphologic measurements. Further investigation into canopy components with increased attention to branching structure is needed before a reliable predictive model for damping ratio is realized.

For practicing arborists who are charged with decreasing the likelihood of tree failure, the results of this study can provide additional insight to guide their recommended prescriptions. While cabling caused an increase in the natural frequency of sample trees, there was no detectable effect on the damping ratios of the sample trees. It is important to remember that pruning was not administered with the cabling treatments, so the complete effect that a pruning and cabling prescription may have on the ability of the tree to dissipate dynamic stress is still unknown. Additionally, trees act as a dynamic system composed of many parts that interact during times of dynamic stress to prevent catastrophic failure from occurring. Before any prescriptions are recommended, it is imperative that the tree be viewed as a dynamic system in order to prevent disruption of any mechanisms that may aid in dissipating dynamic stress.

## **CHAPTER 6**

### **CONCLUSION**

Leaf condition and cabling treatment both had a significant effect on the frequency of sample trees in this study. The effect of cables was not directly comparable to previous studies as it was not encountered in a rigorous literature review, but is in agreement with theoretical physical analyses performed during the experimental design period of this study. The effect of leaf condition on the natural frequency of vibration of the sample trees is in agreement with both theoretical physical analyses and previous investigative efforts. This is also true for the effect of leaf condition on the damping ratio of the sample trees, though there is a limited amount of previous research on large deciduous trees available for comparison.

A logical next step is to test the effect that pruning treatments in conjunction with cable installation have on the dynamic properties of open grown deciduous trees. It would also be beneficial to test the effect that multiple cables have on the dynamic properties of trees, as many historically valued trees have multiple cables for additional support.

Finally, investigating deviation from the guidelines set forth in the ANSI A300 Standard for Tree and Woody Shrub Artificial Support Systems (Anonymous 2006) may help to provide better guidelines for cable installation, or provide empiric support for the current guidelines. Deviations of interest would involve varying cable height from the standard  $2/3$  distance between the co-dominant union and top of the shorter branch as well investigating the effect of different cable tensions.

Finite element modeling can provide insight into the mechanisms by which trees are dissipating dynamic stresses as well as allow the researcher to investigate changes in aerial morphology and canopy reconfiguration that could not be performed in the field. Finite element modeling techniques, as well as experimental data gathered on large deciduous trees, can help provide practicing arborists with a more extensive understanding of the dynamic behavior of trees. Future research should strive to extend this knowledge with the end goal of making hazard tree assessment a more objective endeavor in order to better mitigate risk incurred by the general public.

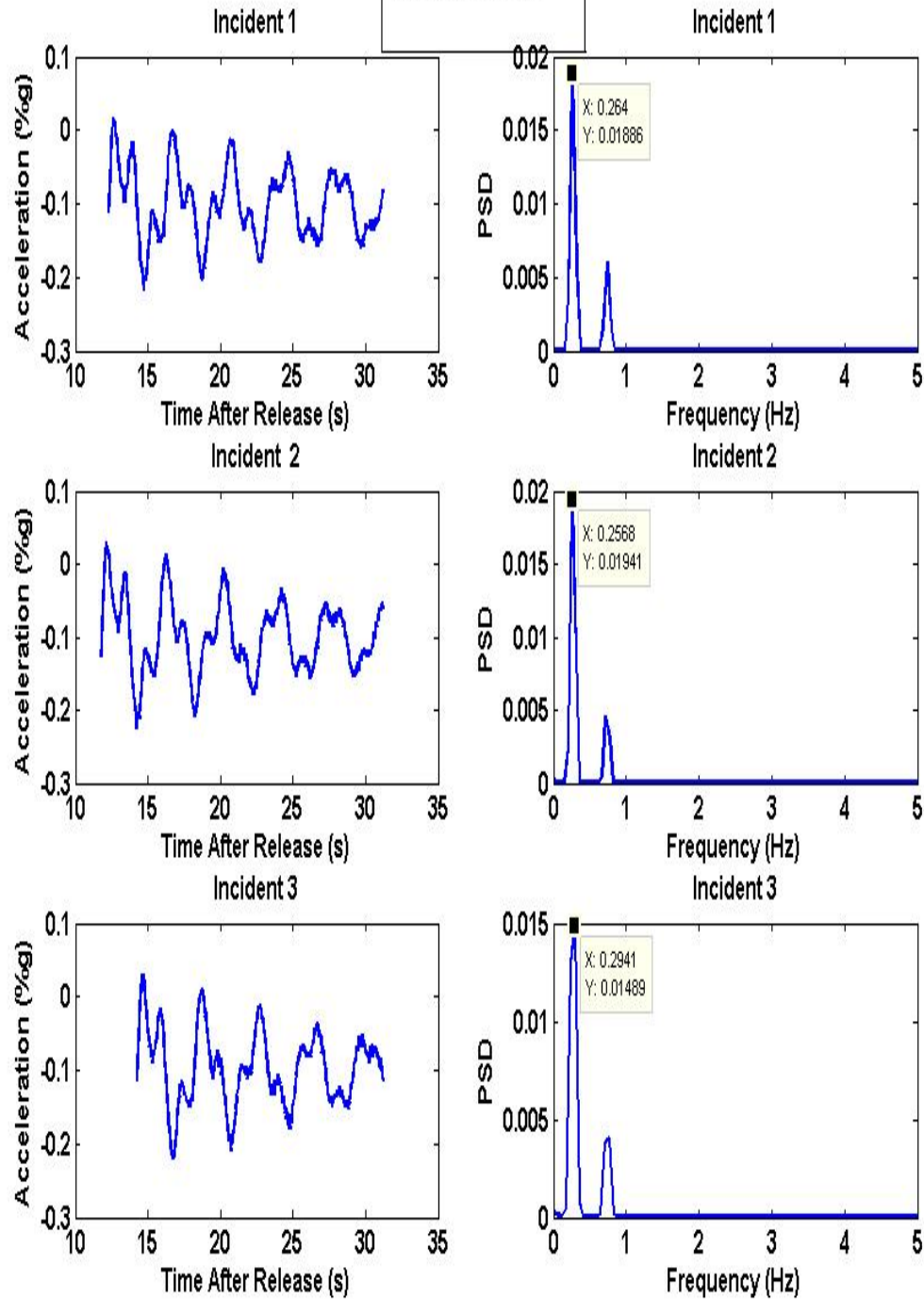
**APPENDIX A**

**ACCELERATION VS TIME HISTORY AND POWER SPECTRAL DENSITY**

**PLOTS**

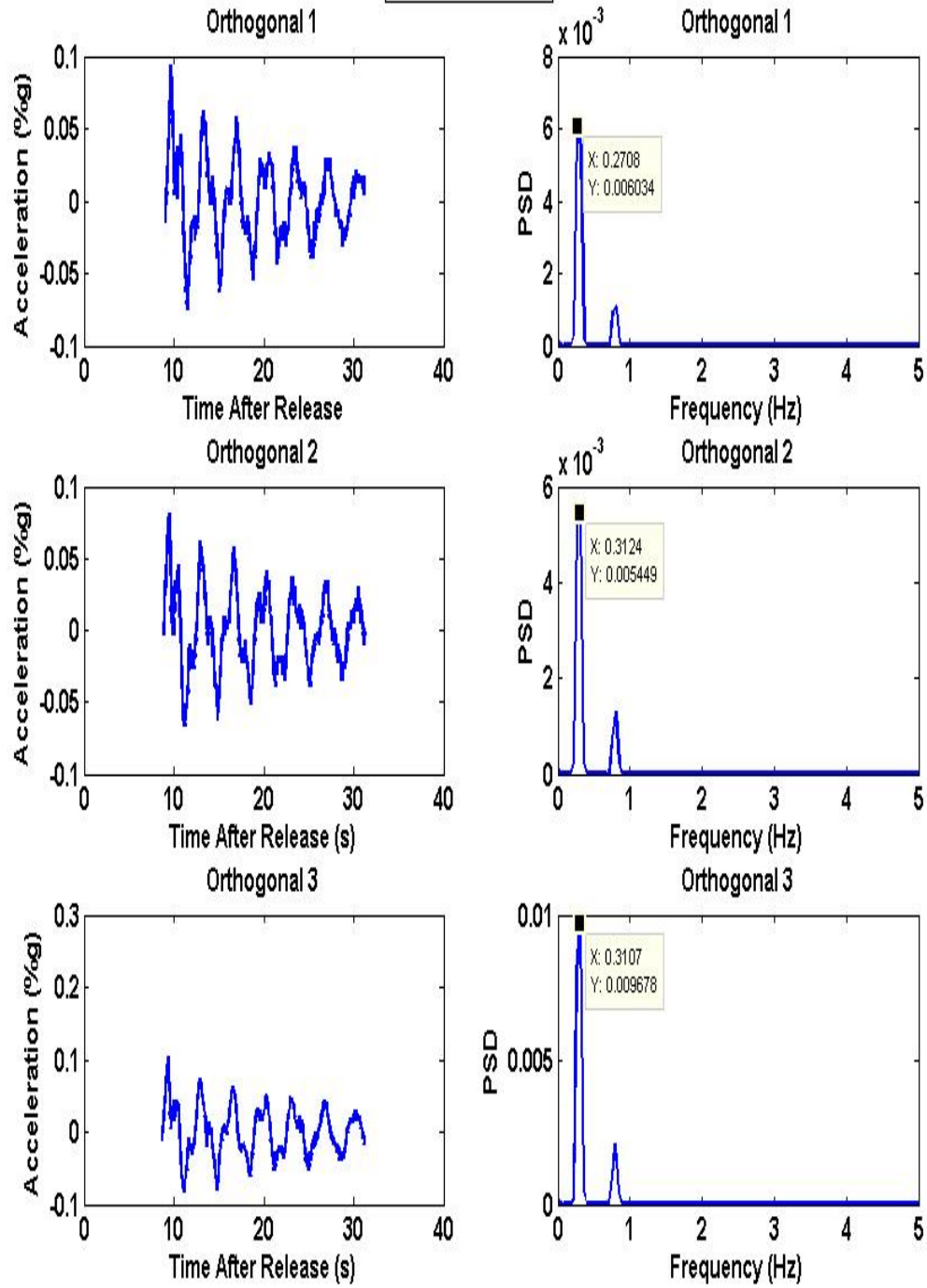
## Leaf Off

### Tree 50 Leaf Off

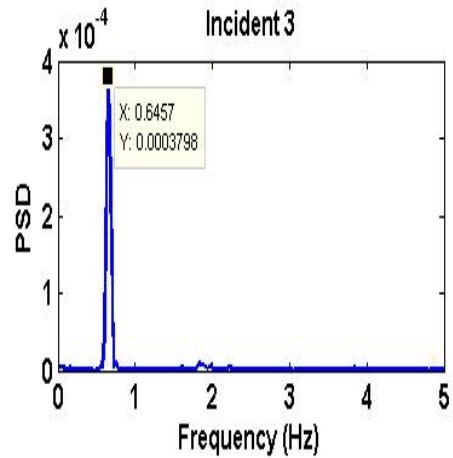
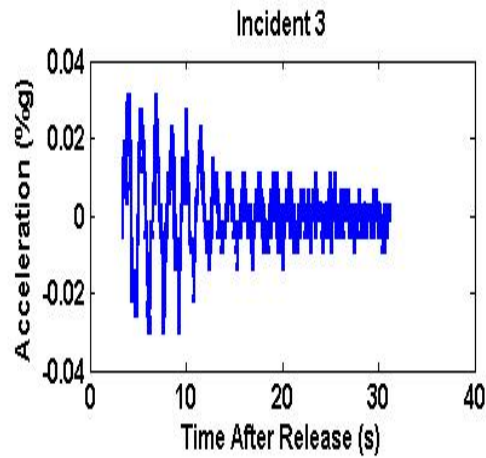
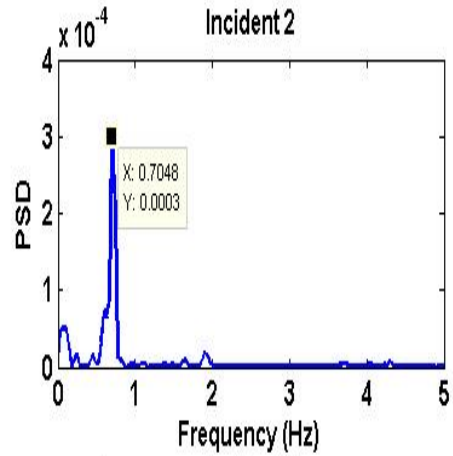
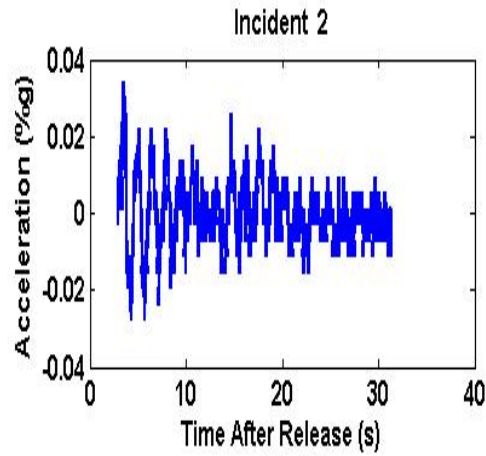
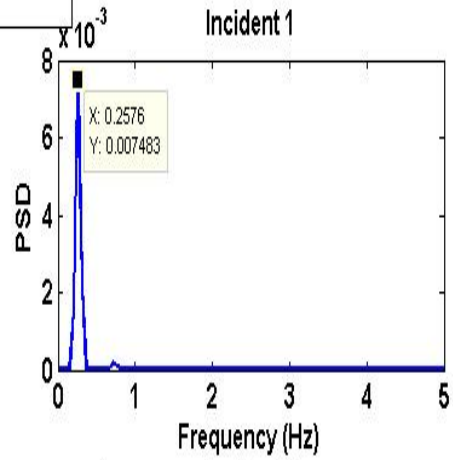
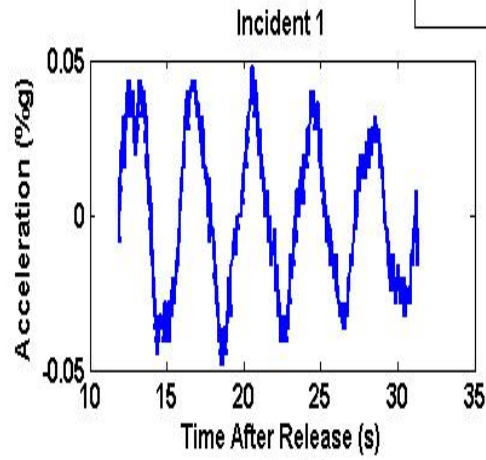




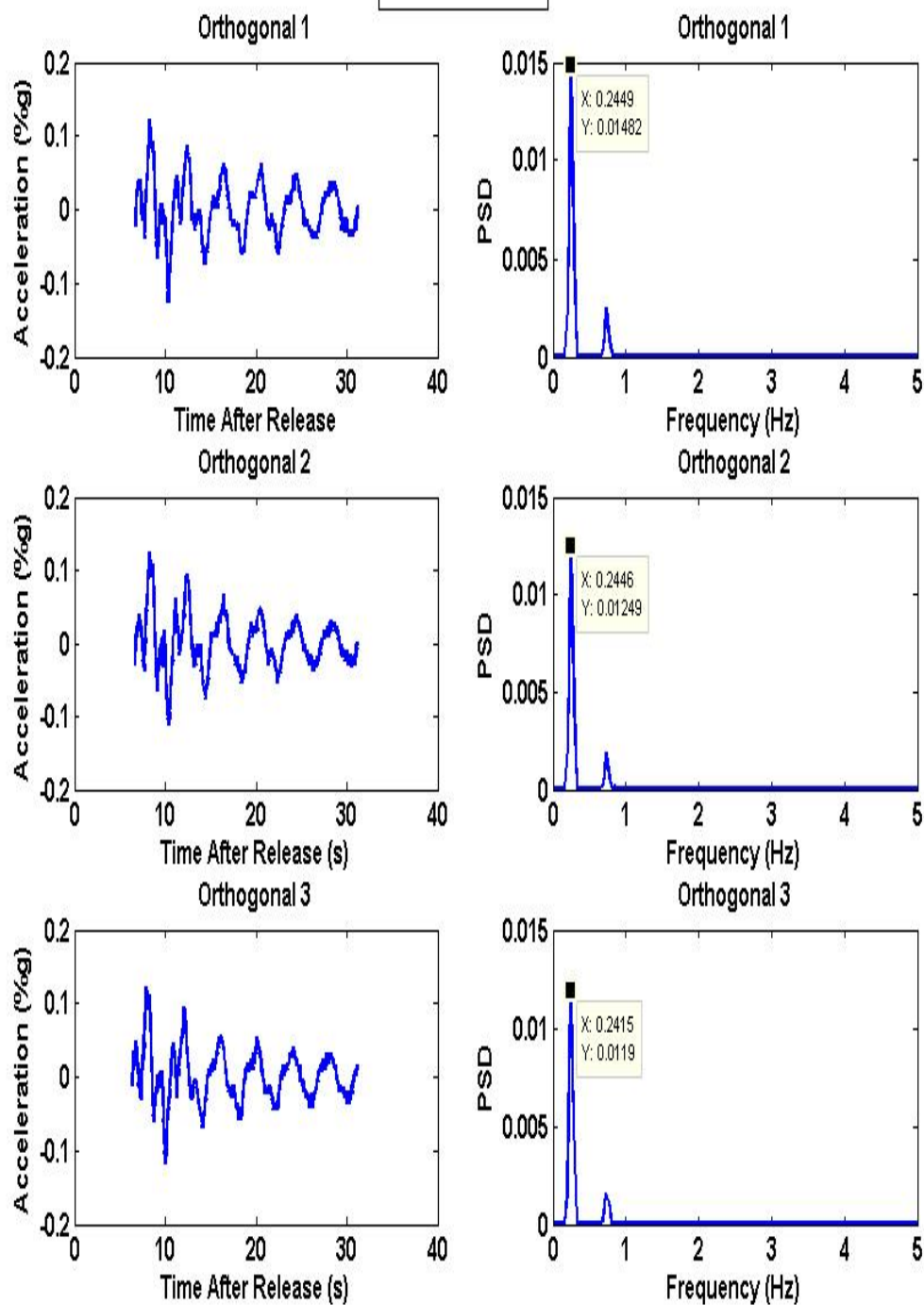
Tree 50 Leaf Off



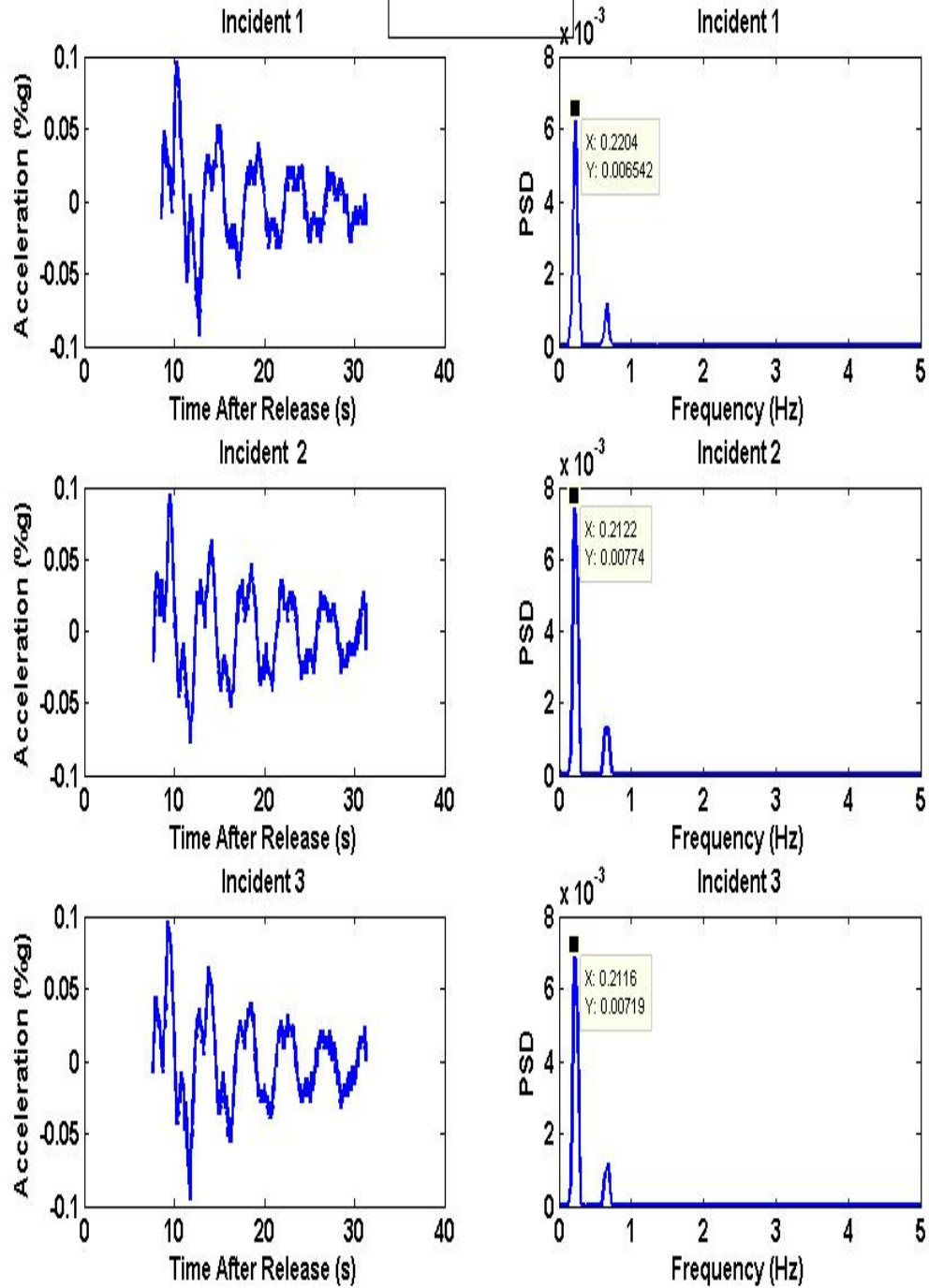
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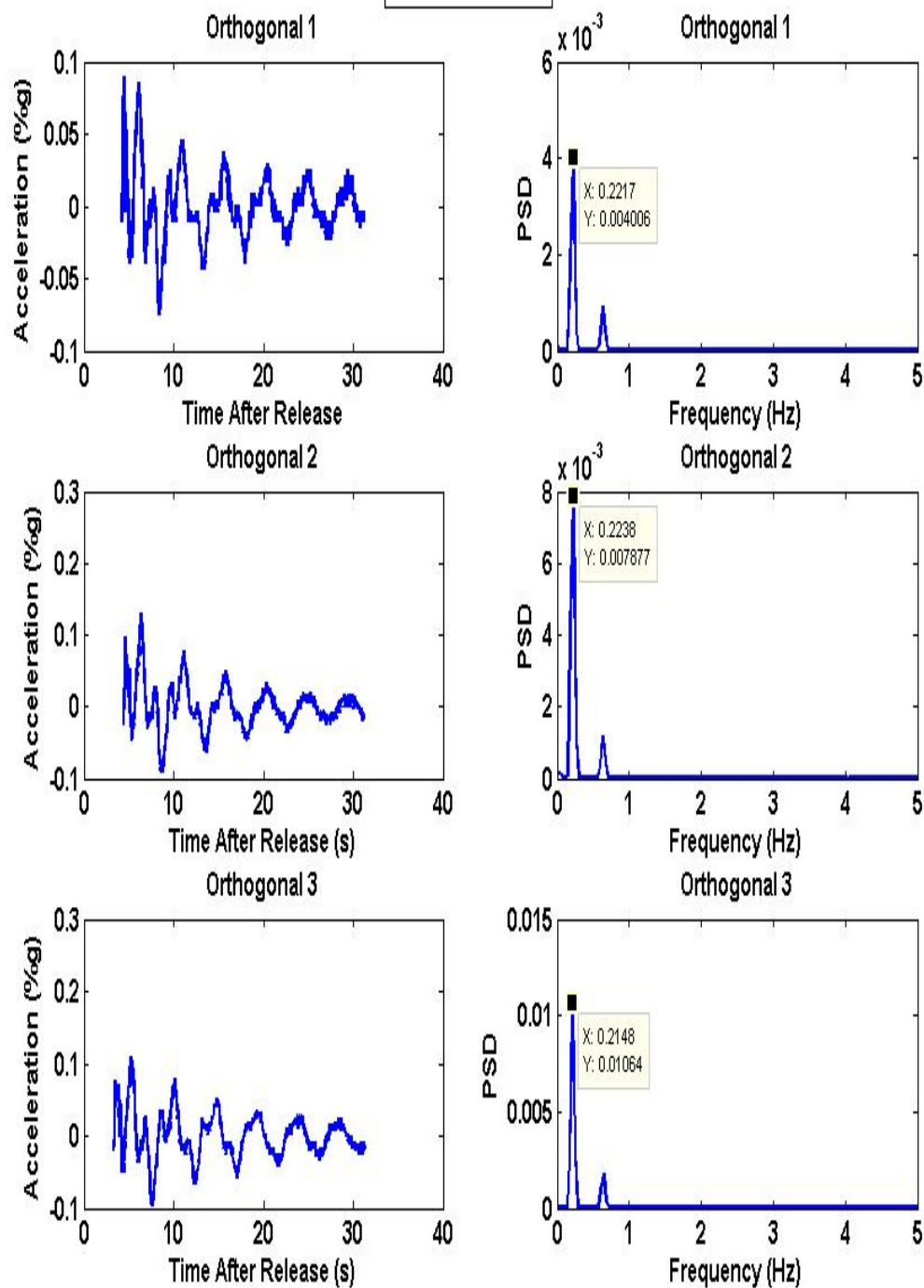
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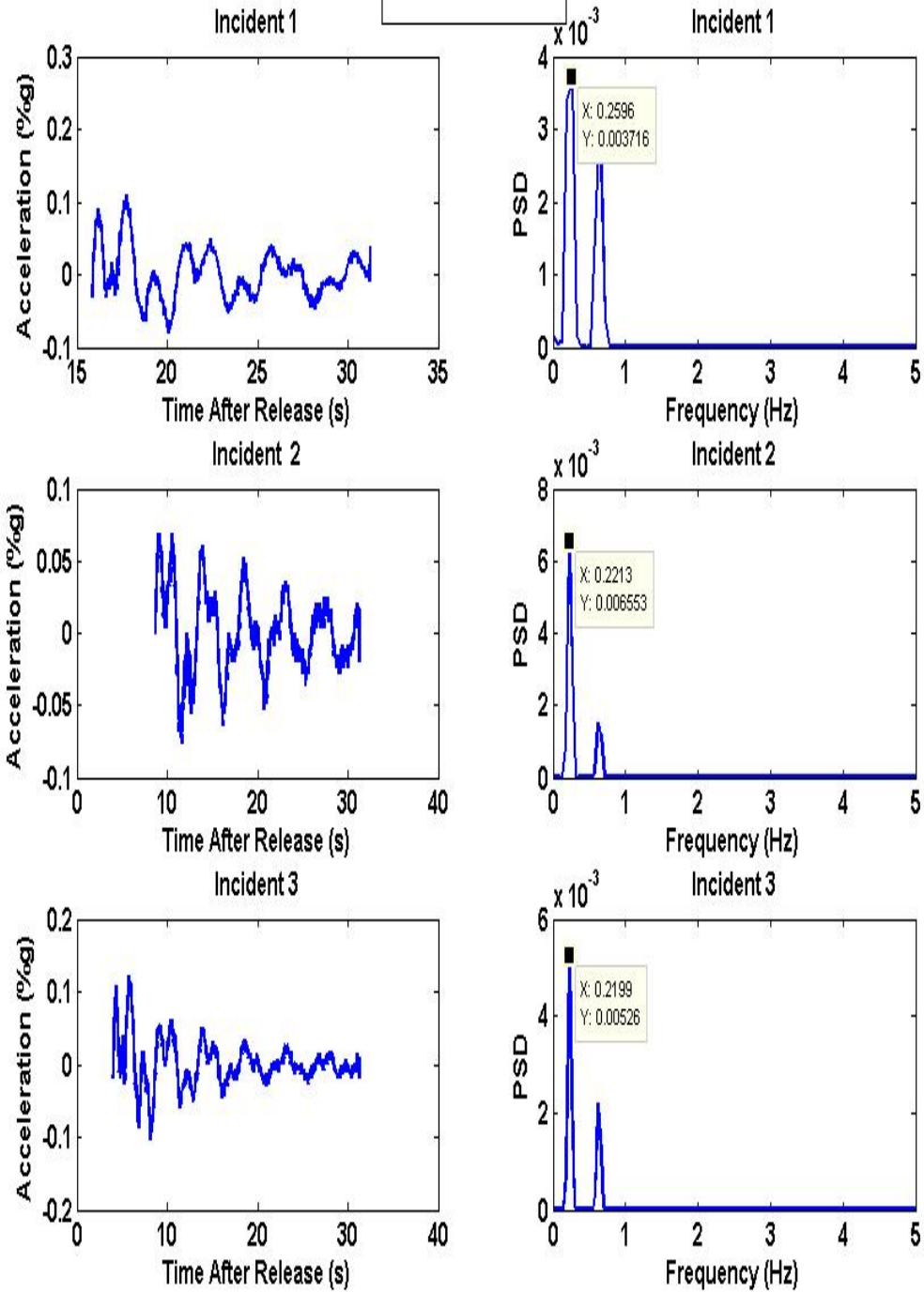
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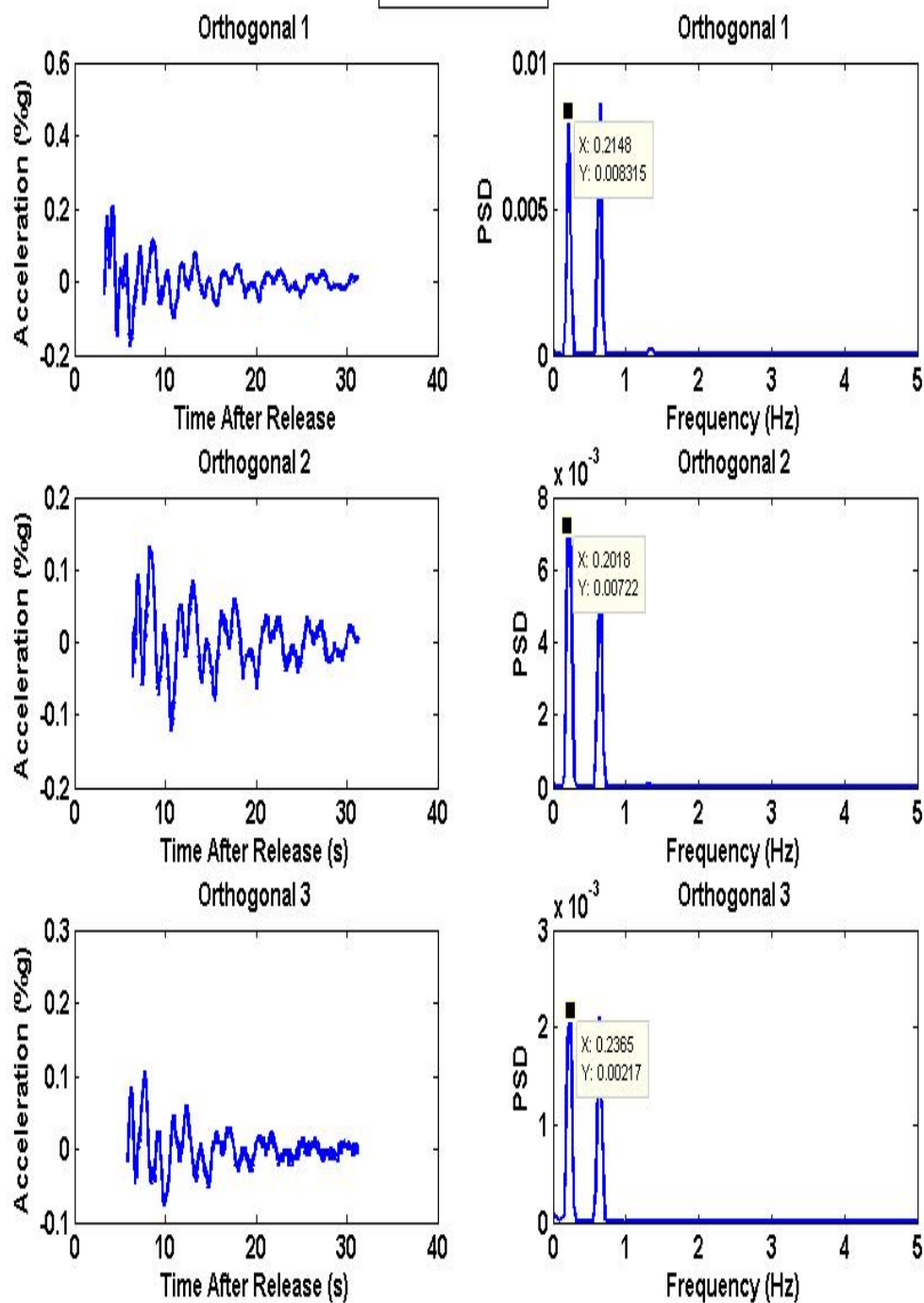
# Tree 52 Leaf Off



# Tree 53 Leaf Off

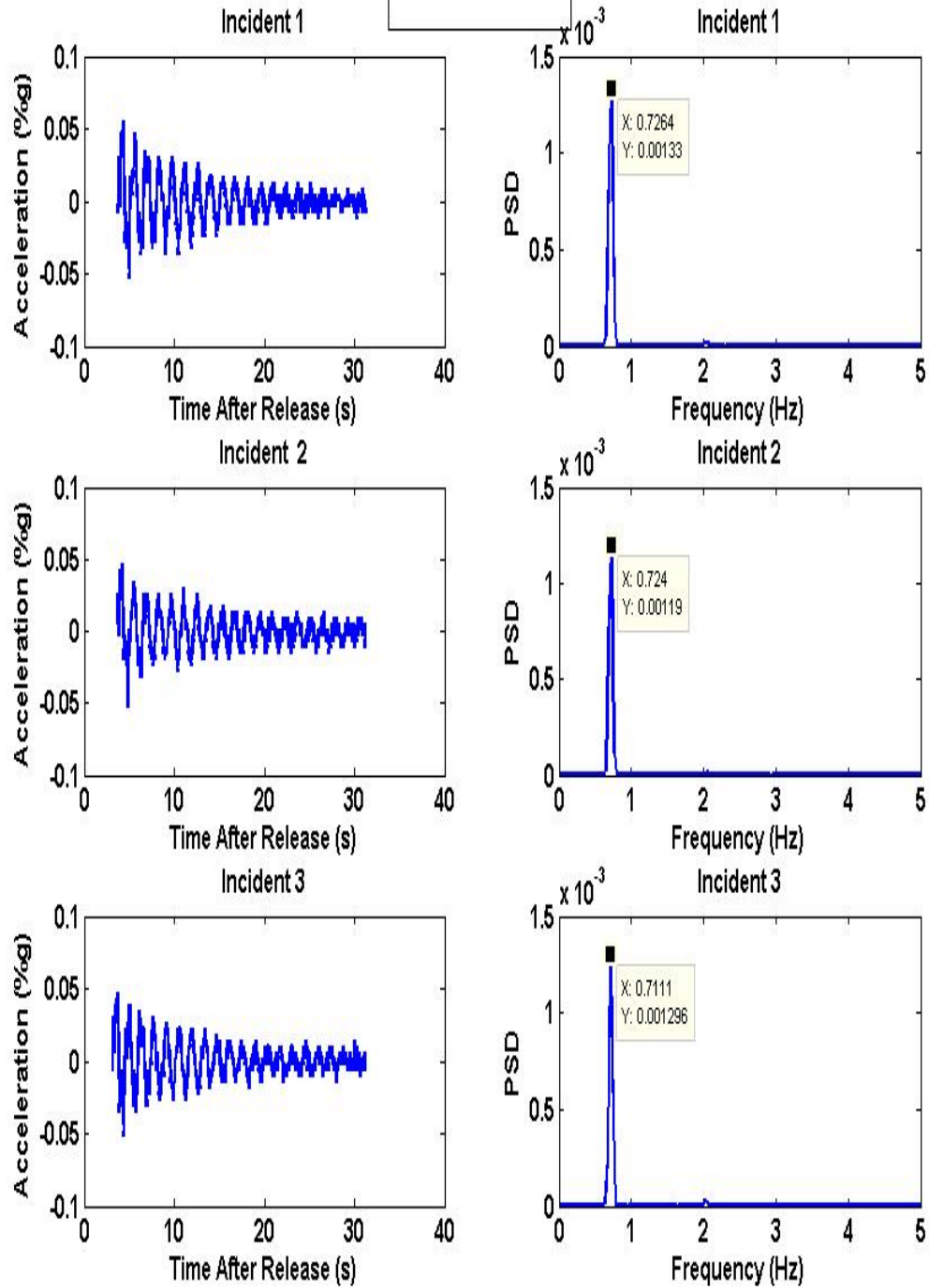


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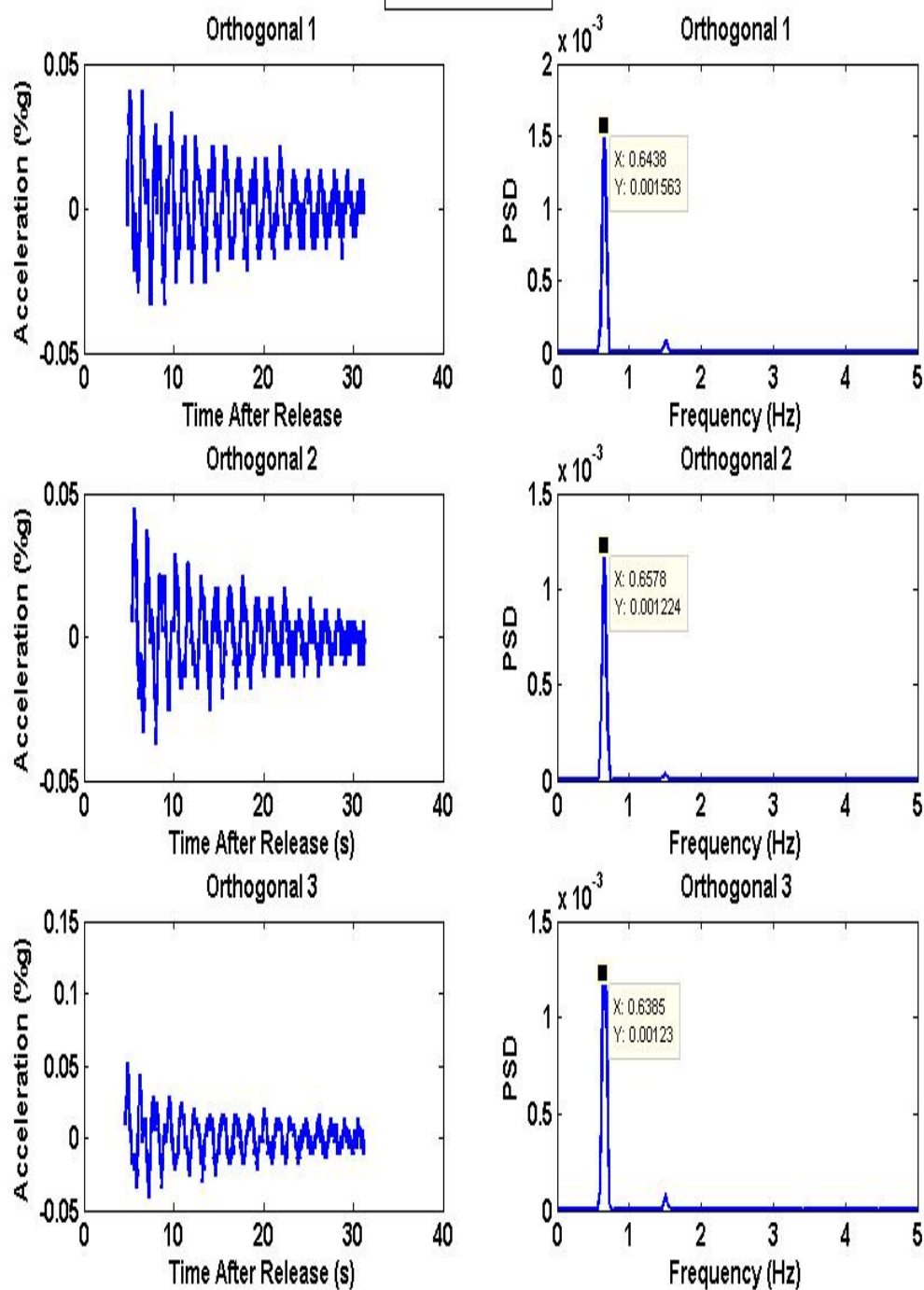


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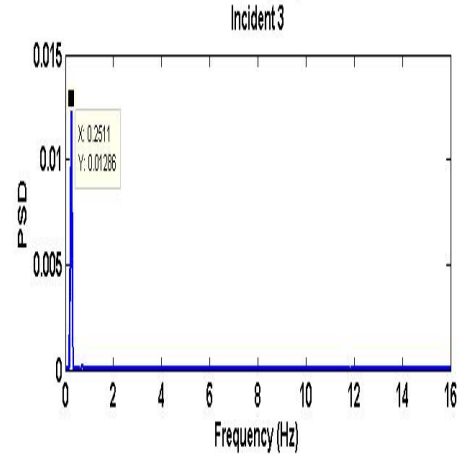
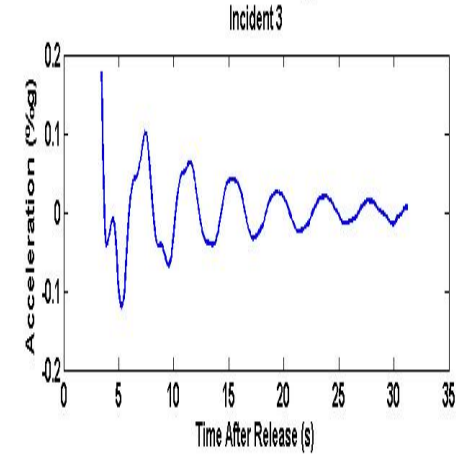
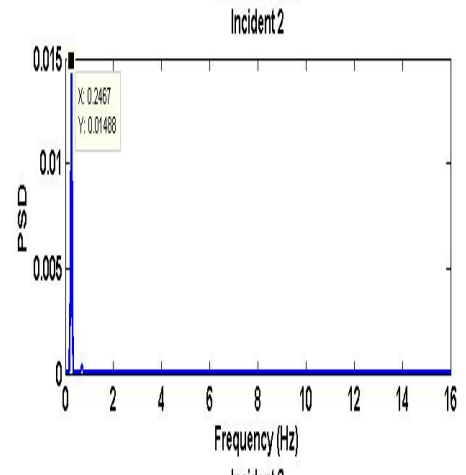
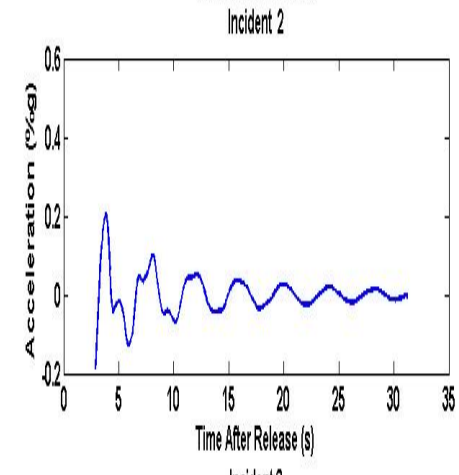
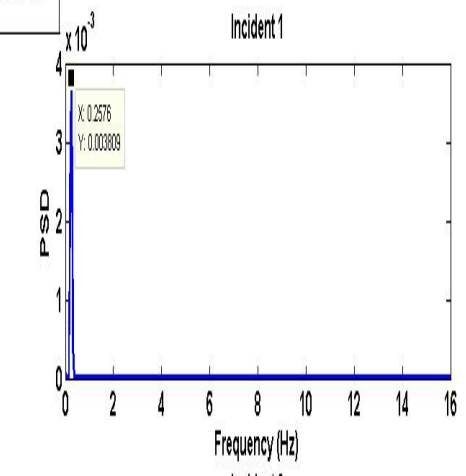
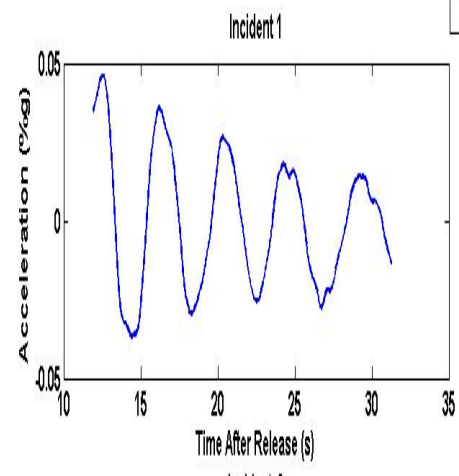


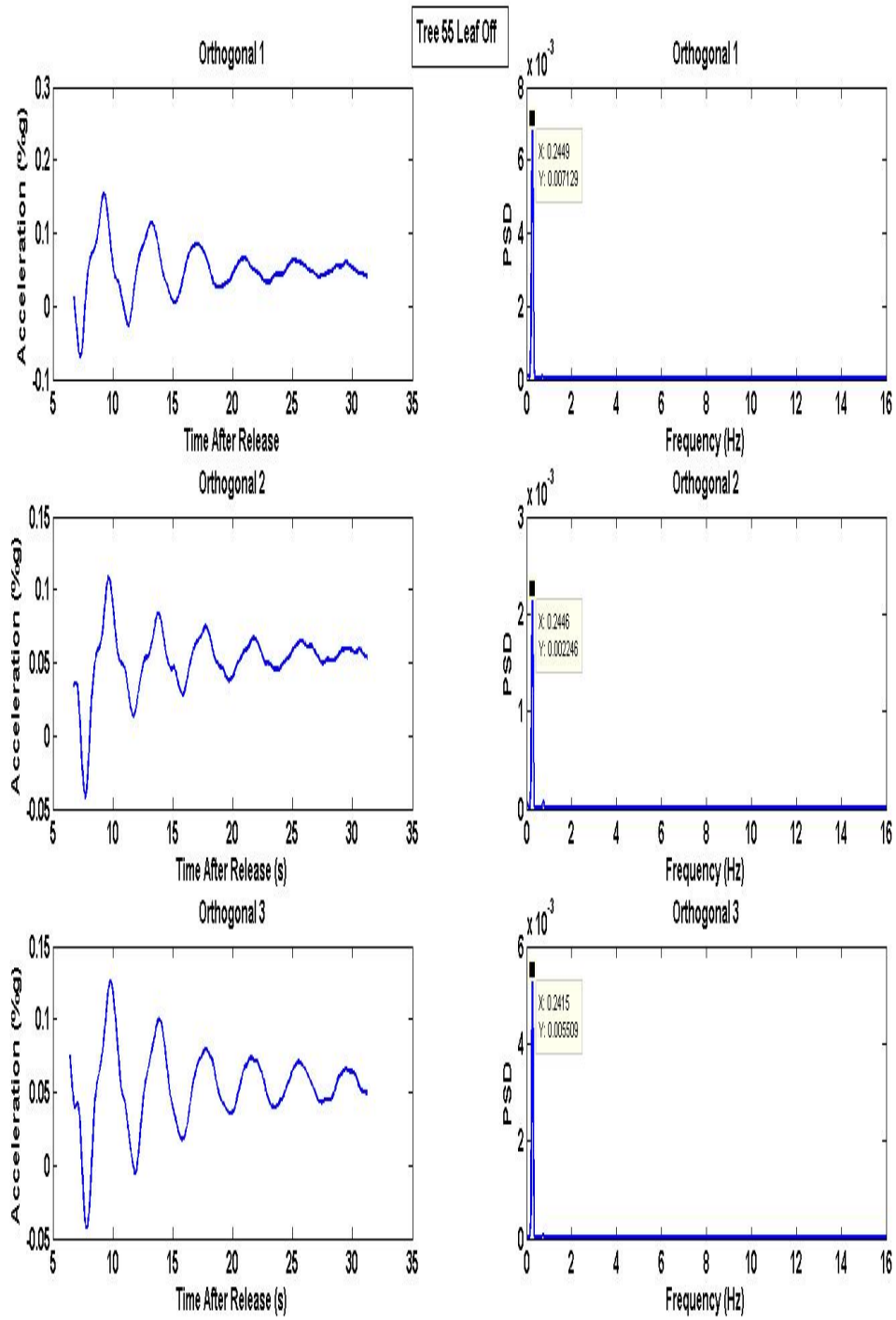


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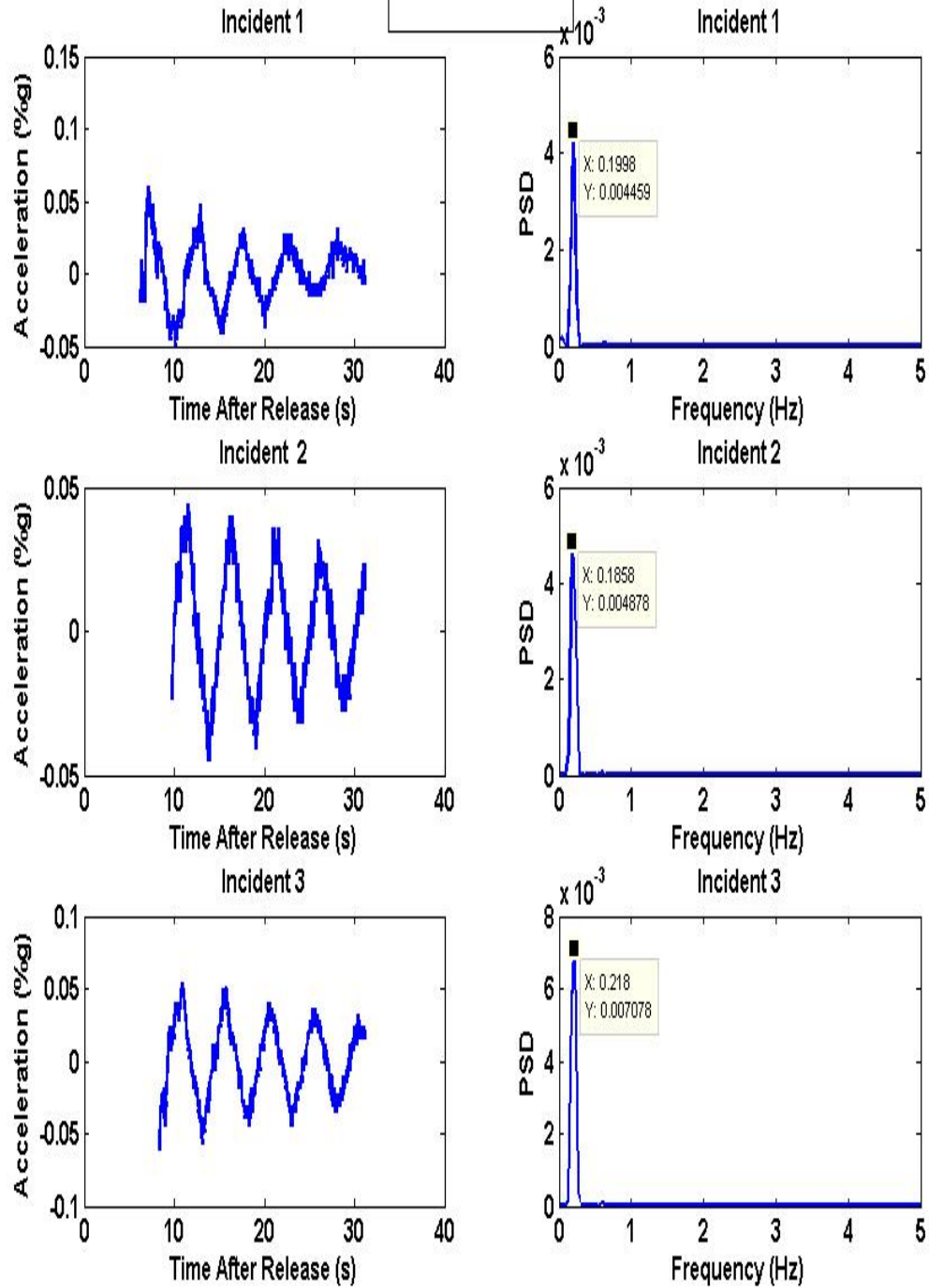


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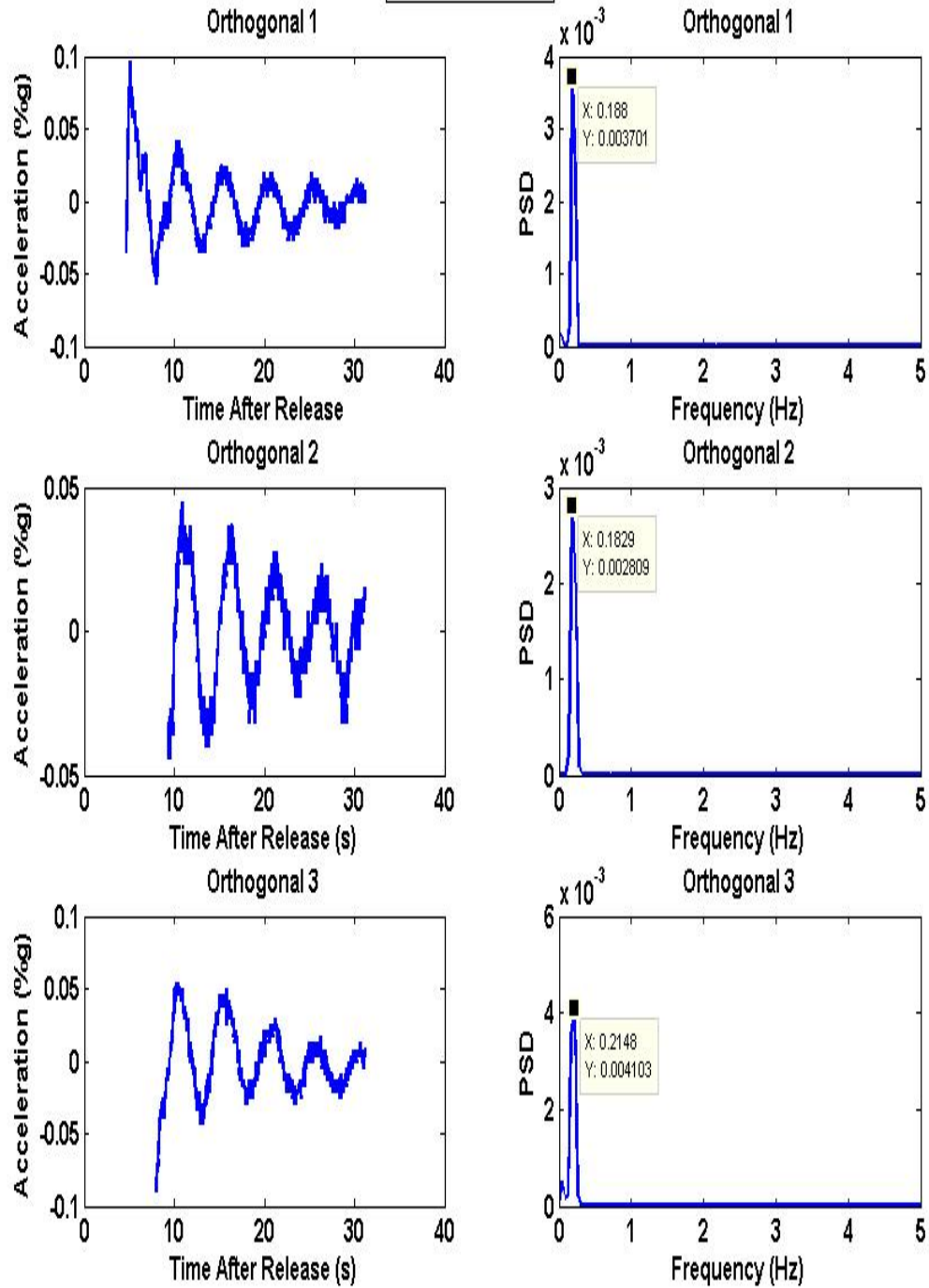




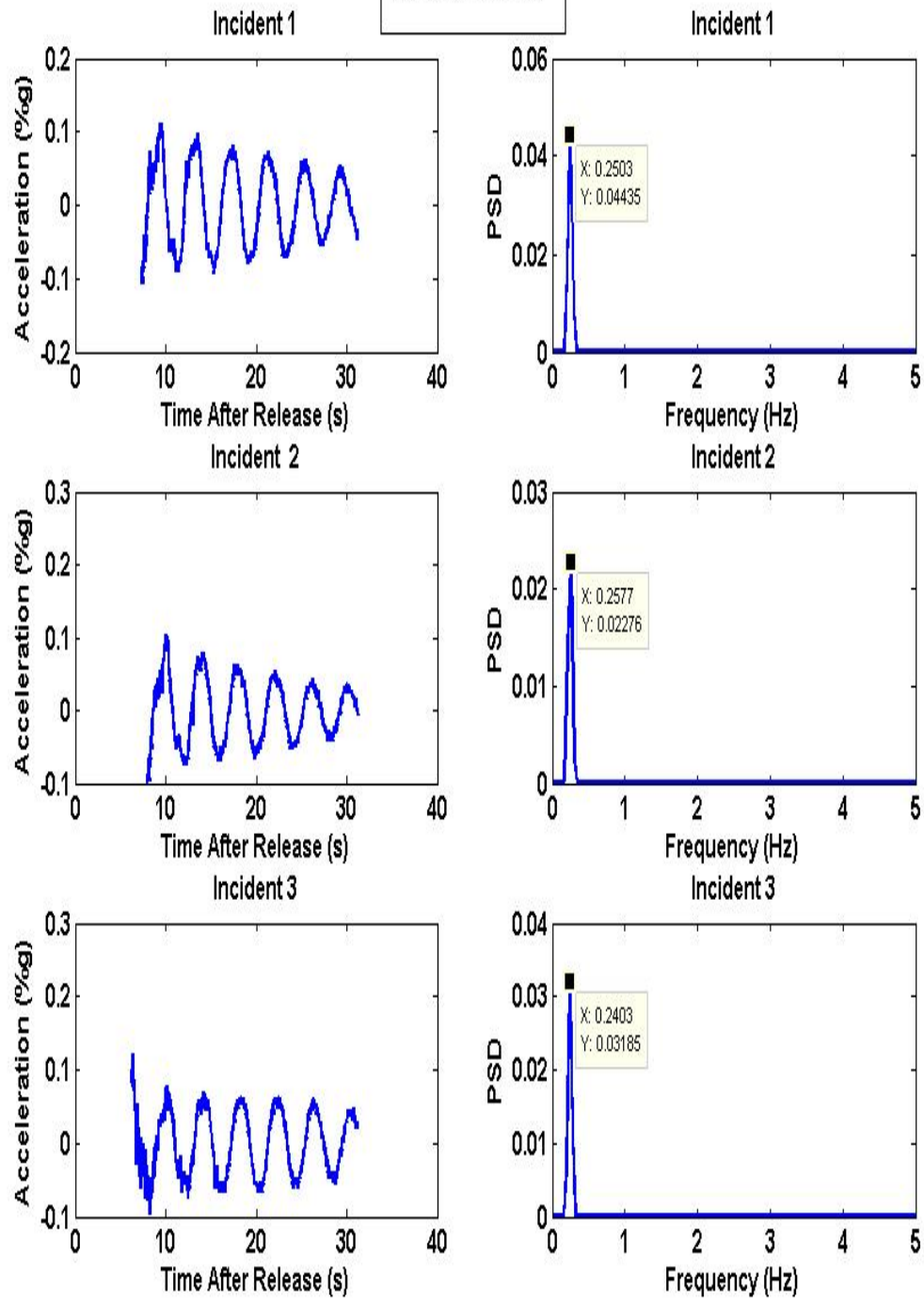
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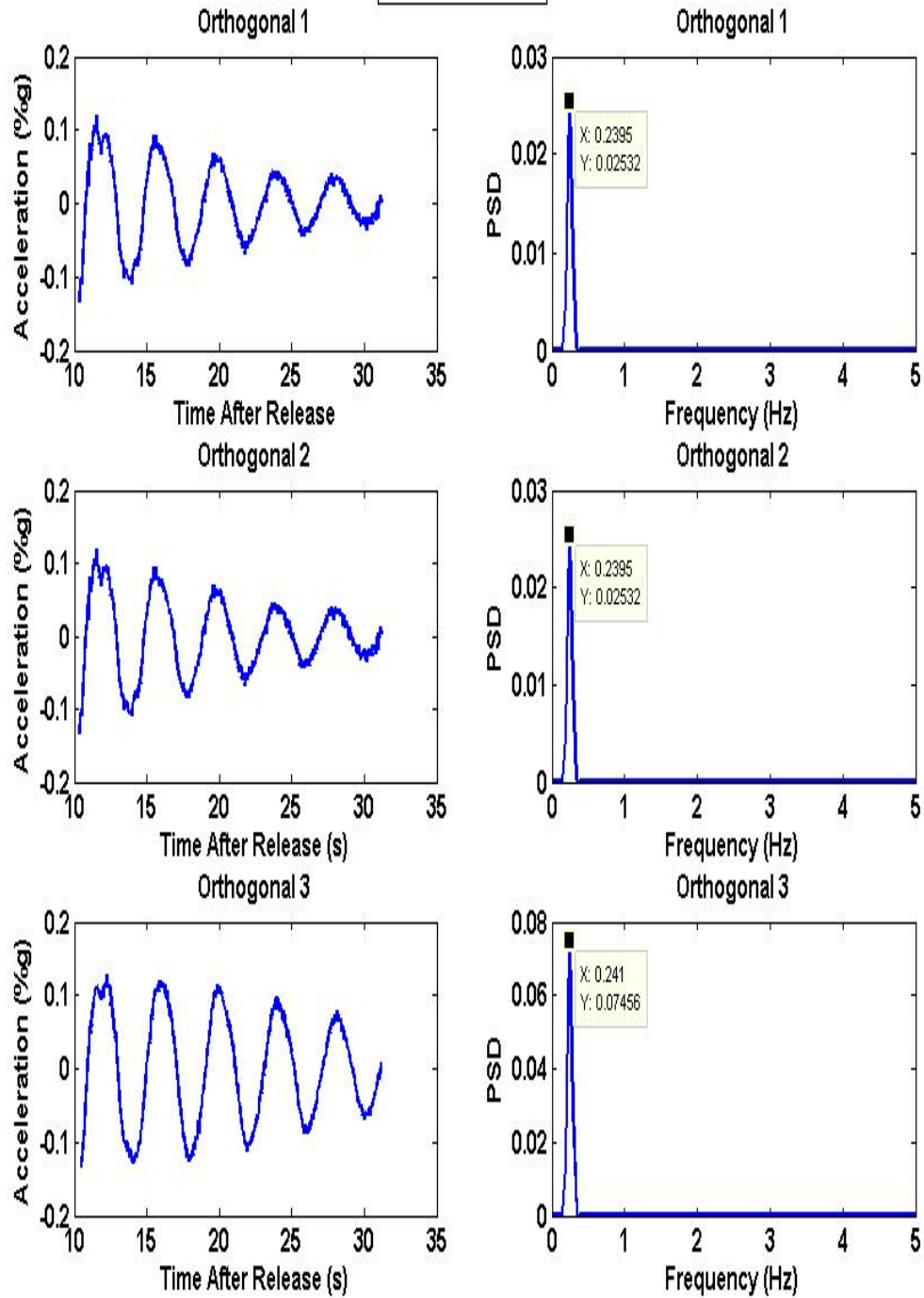
Tree 56 Leaf Off



### Tree 58 Leaf Off

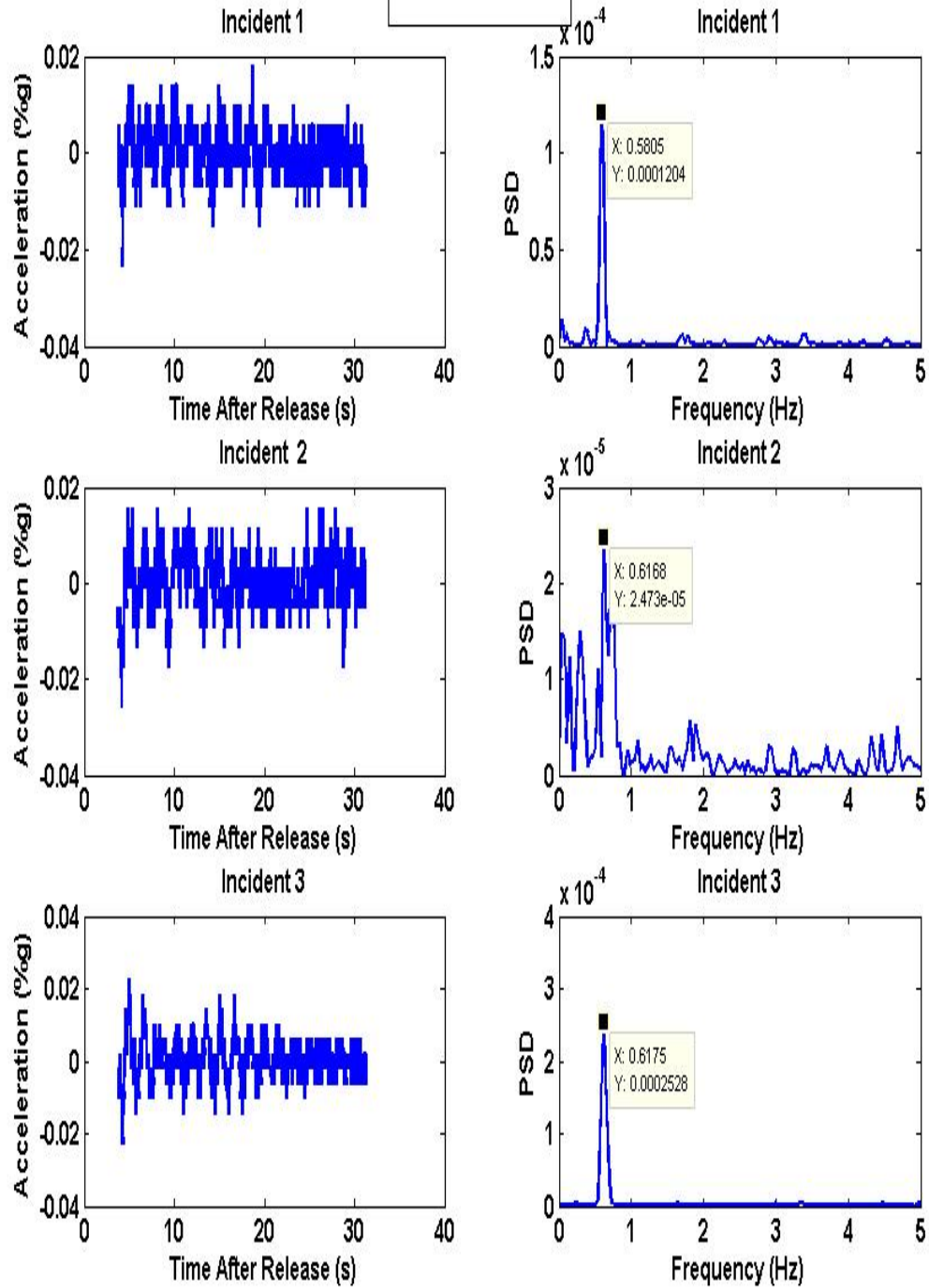


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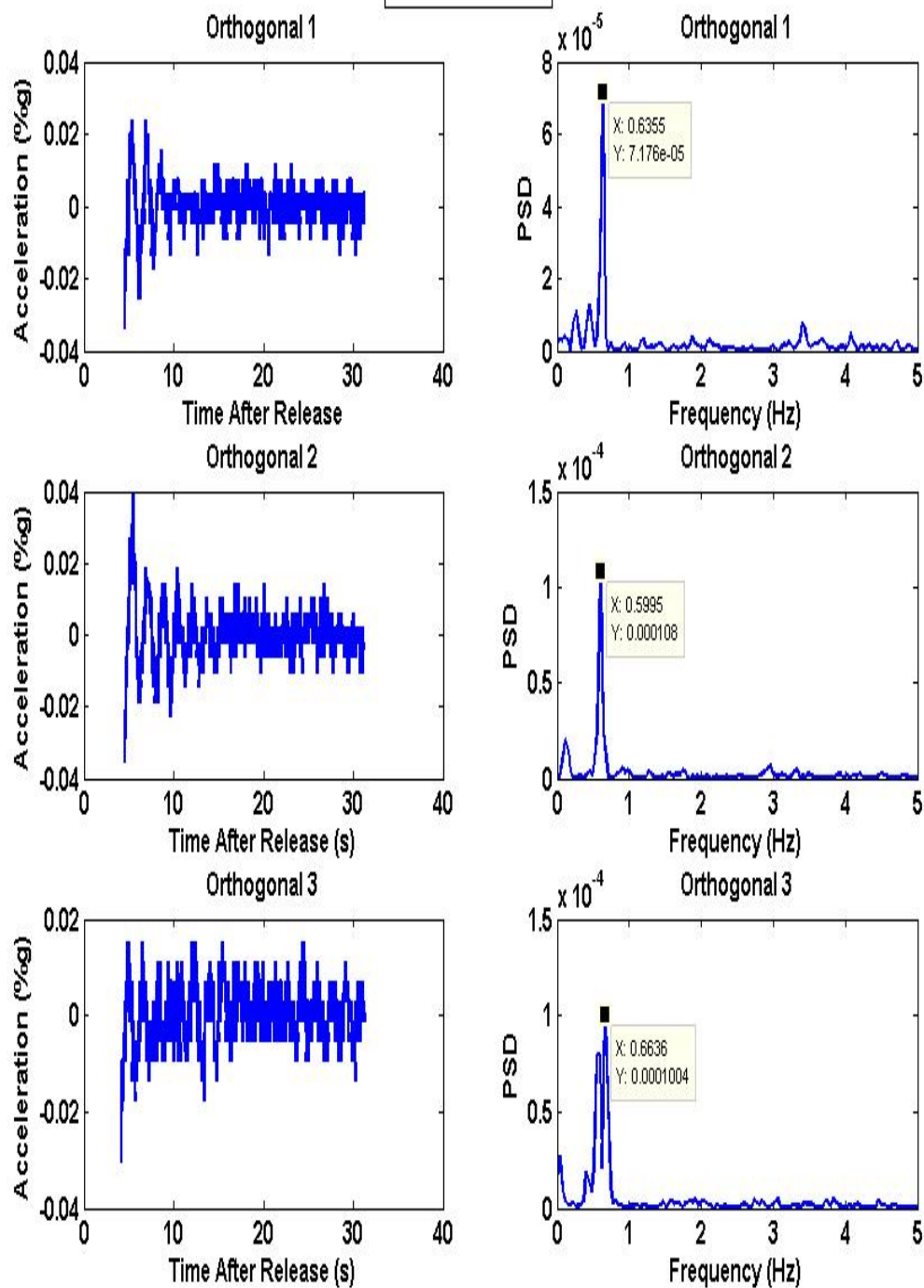


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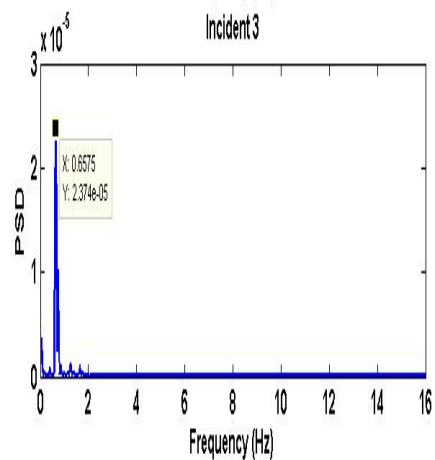
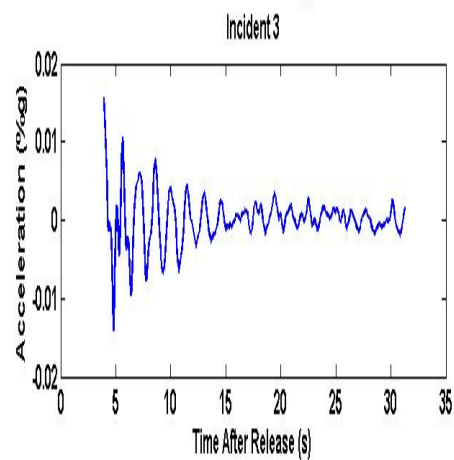
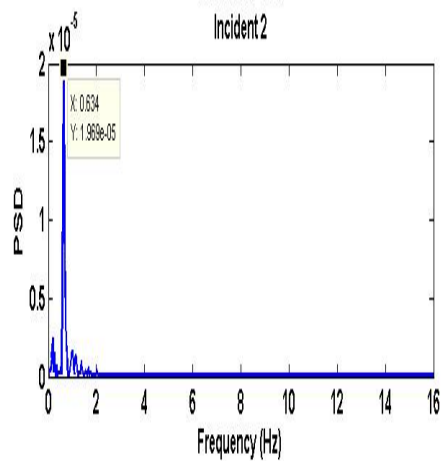
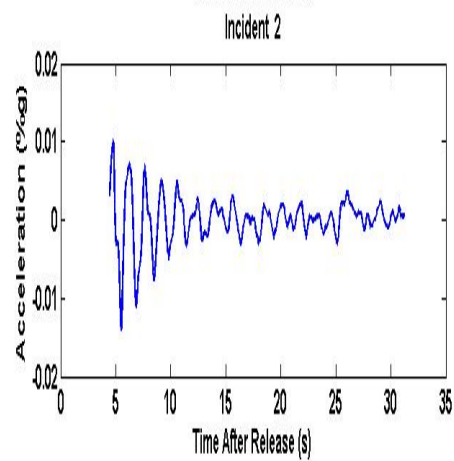
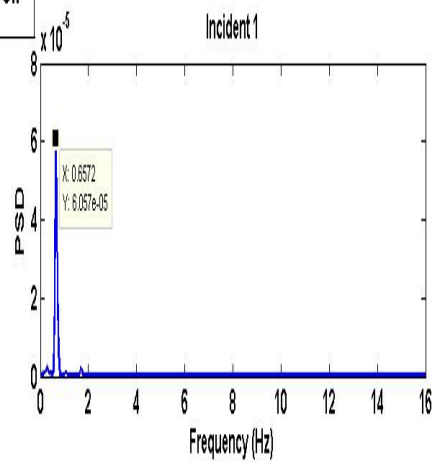
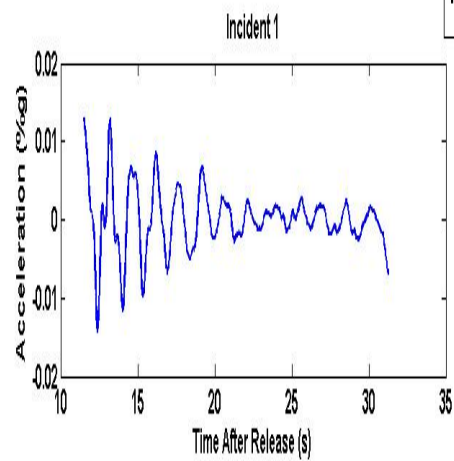




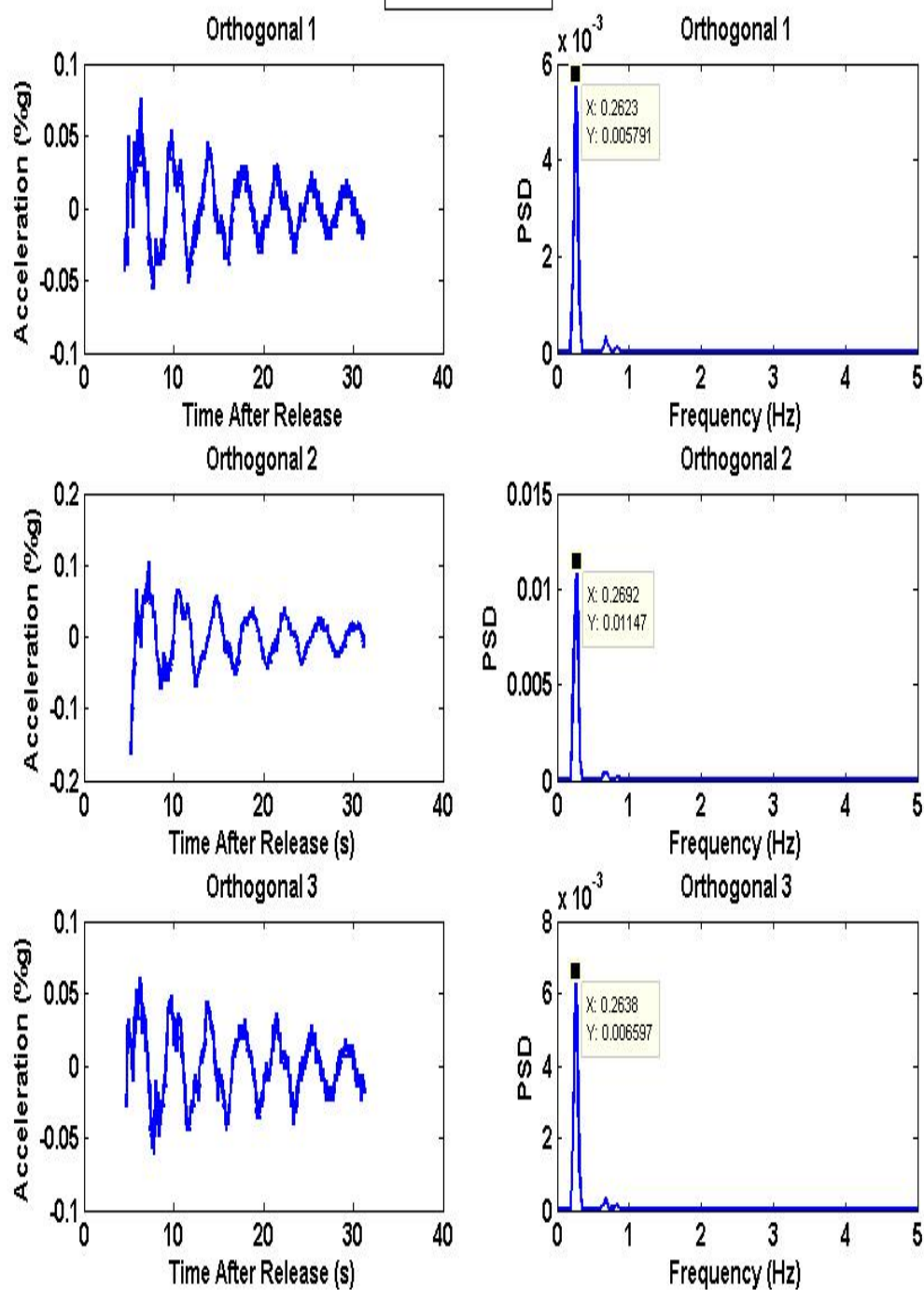
# Tree 59 Leaf Off



Tree 61 Leaf Off

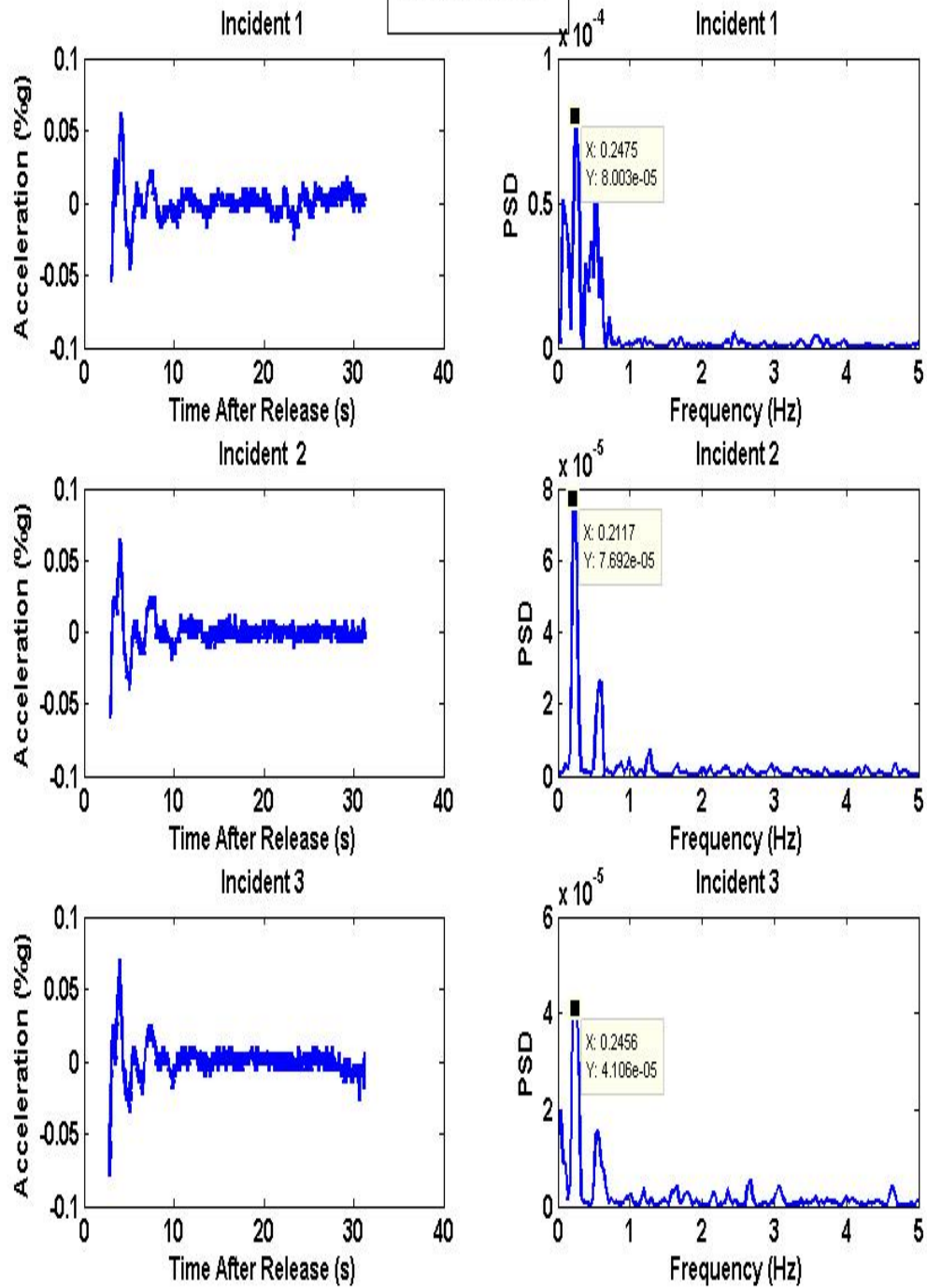


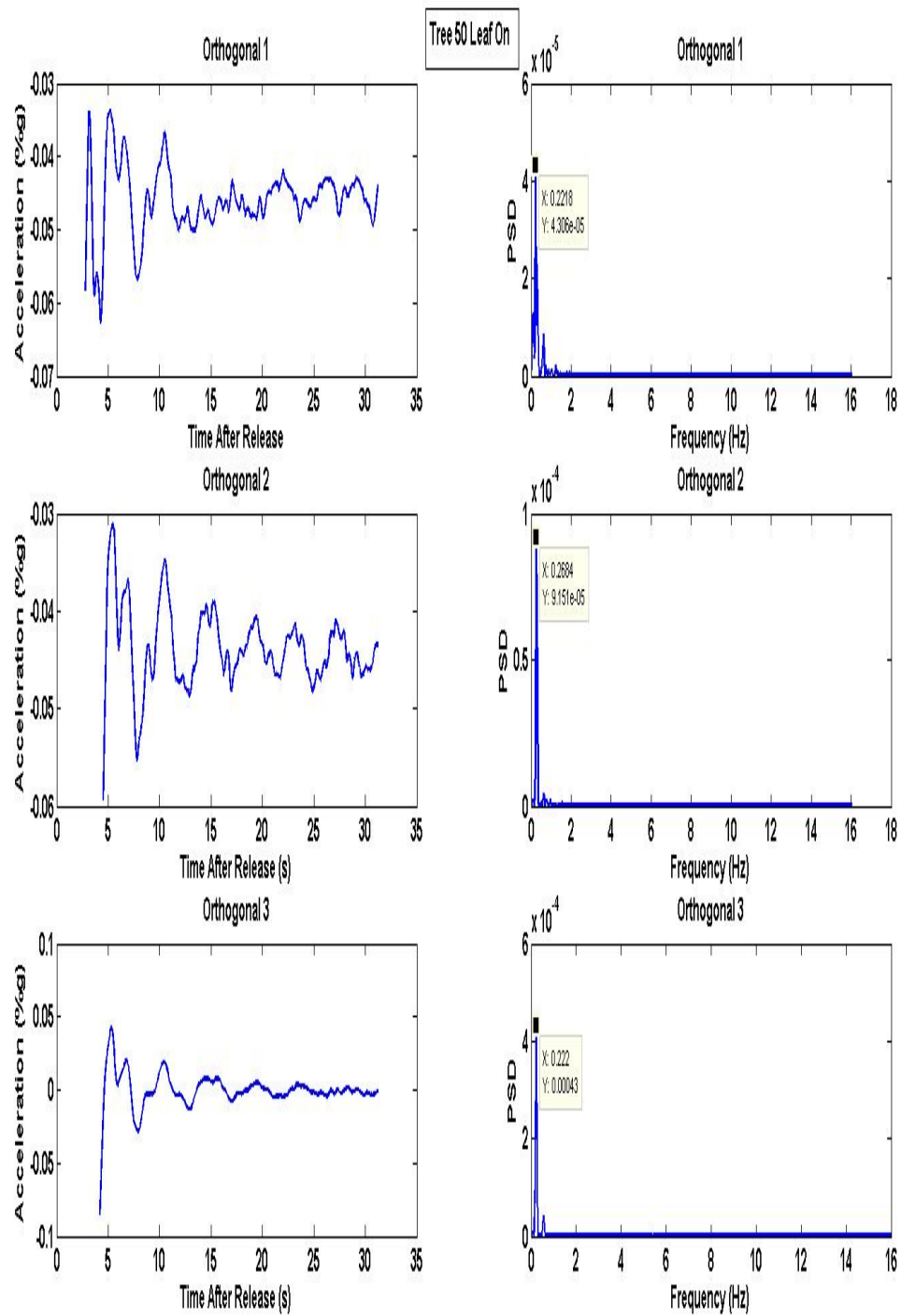
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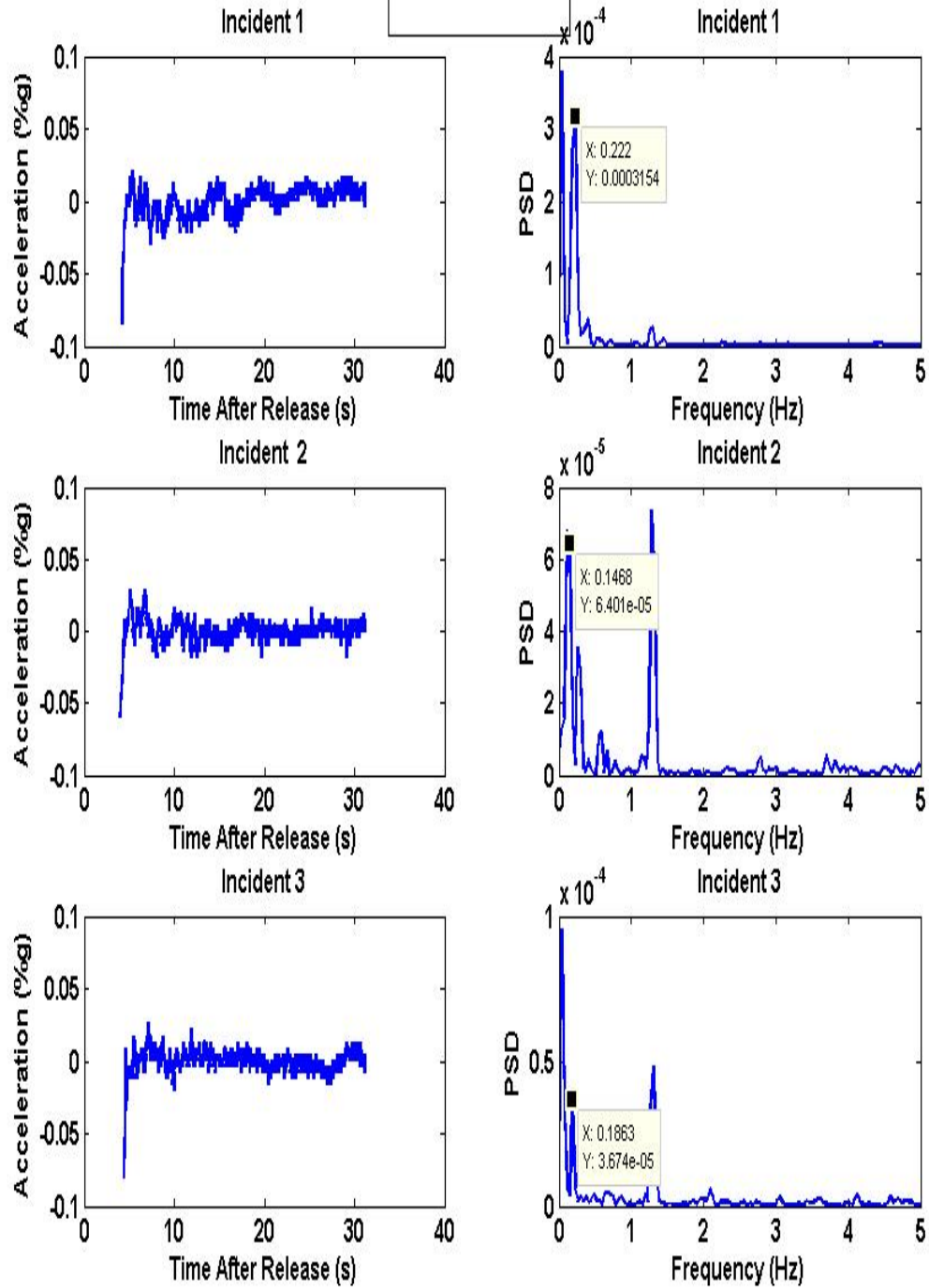
## Leaf On

Tree 50 Leaf On

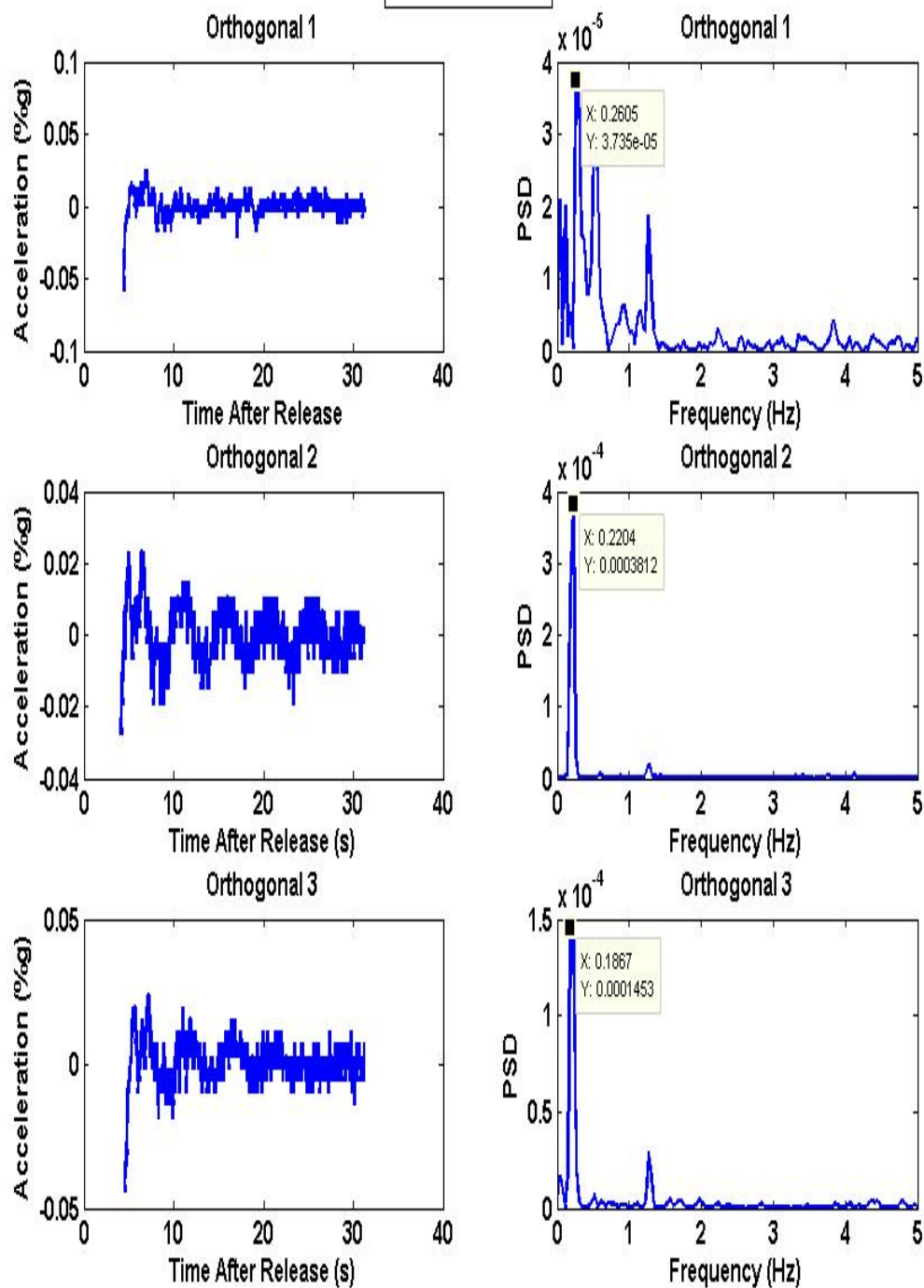




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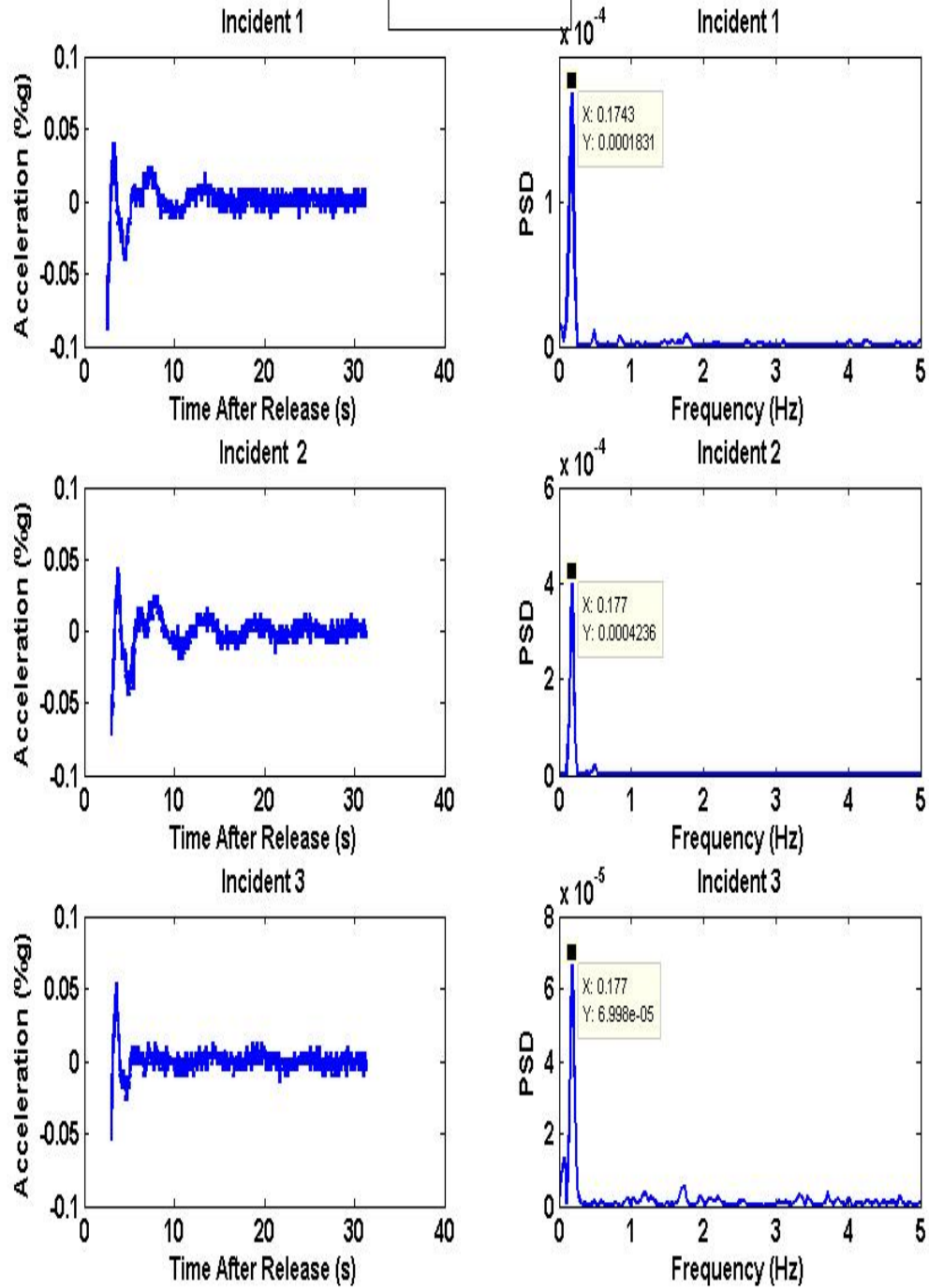


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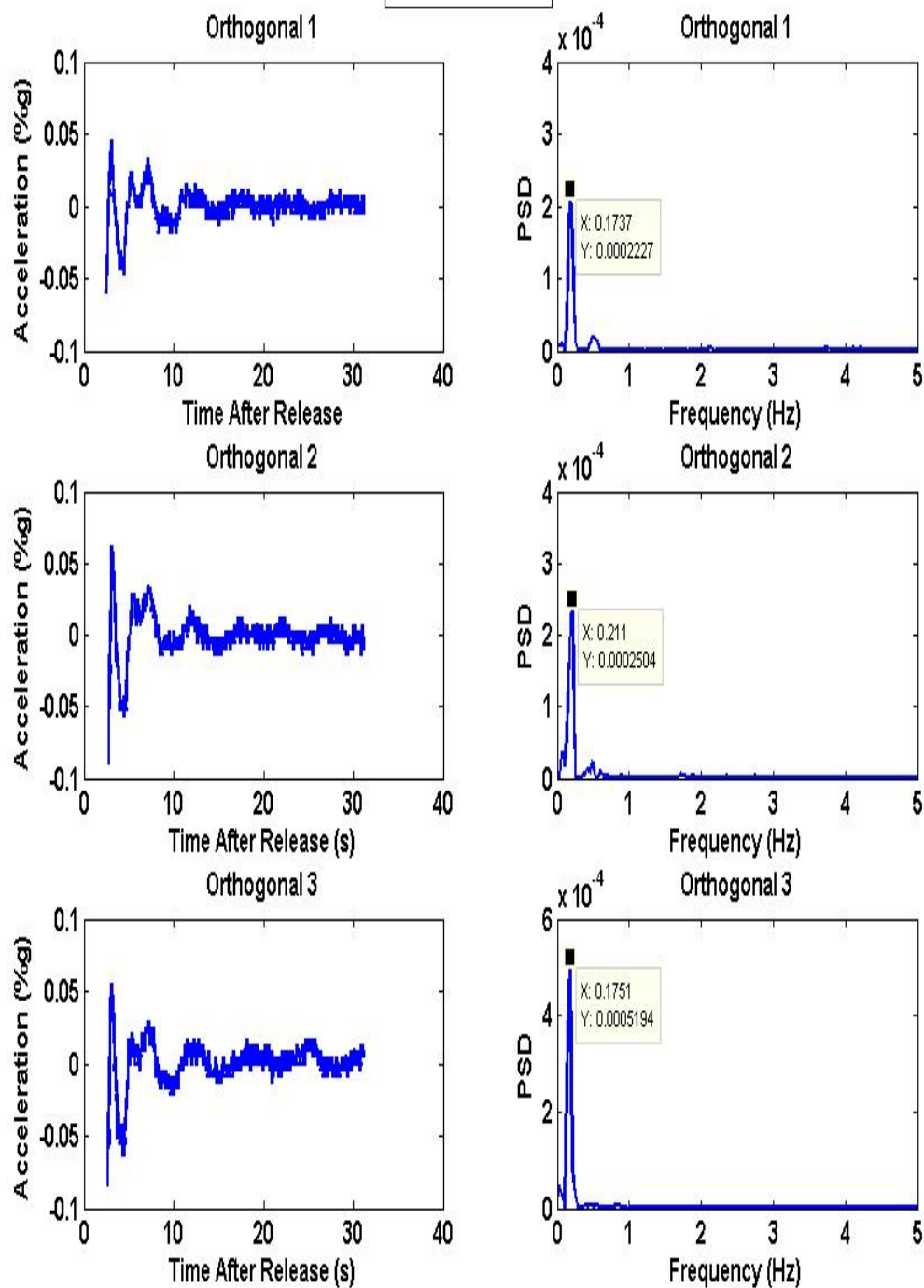


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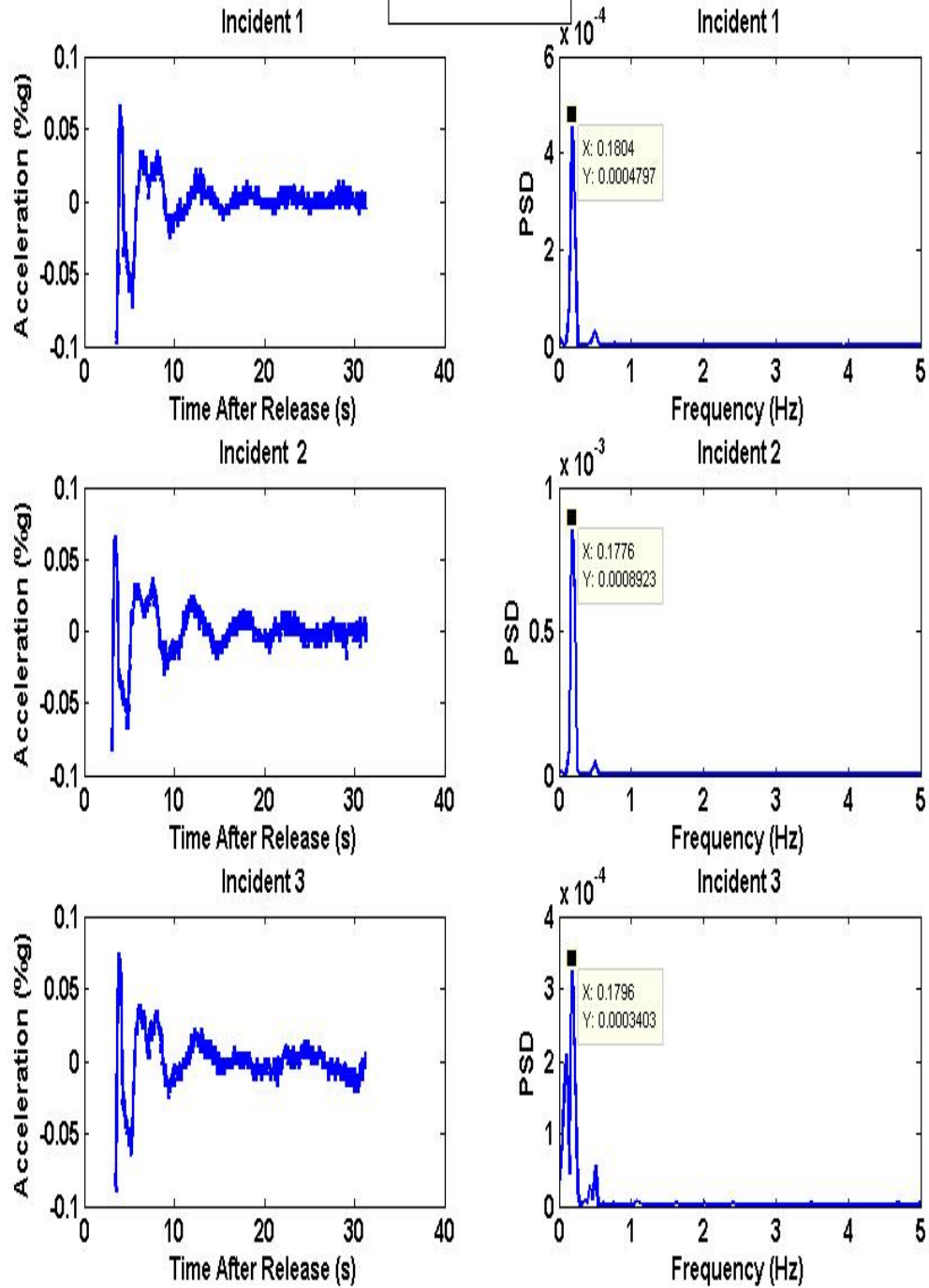




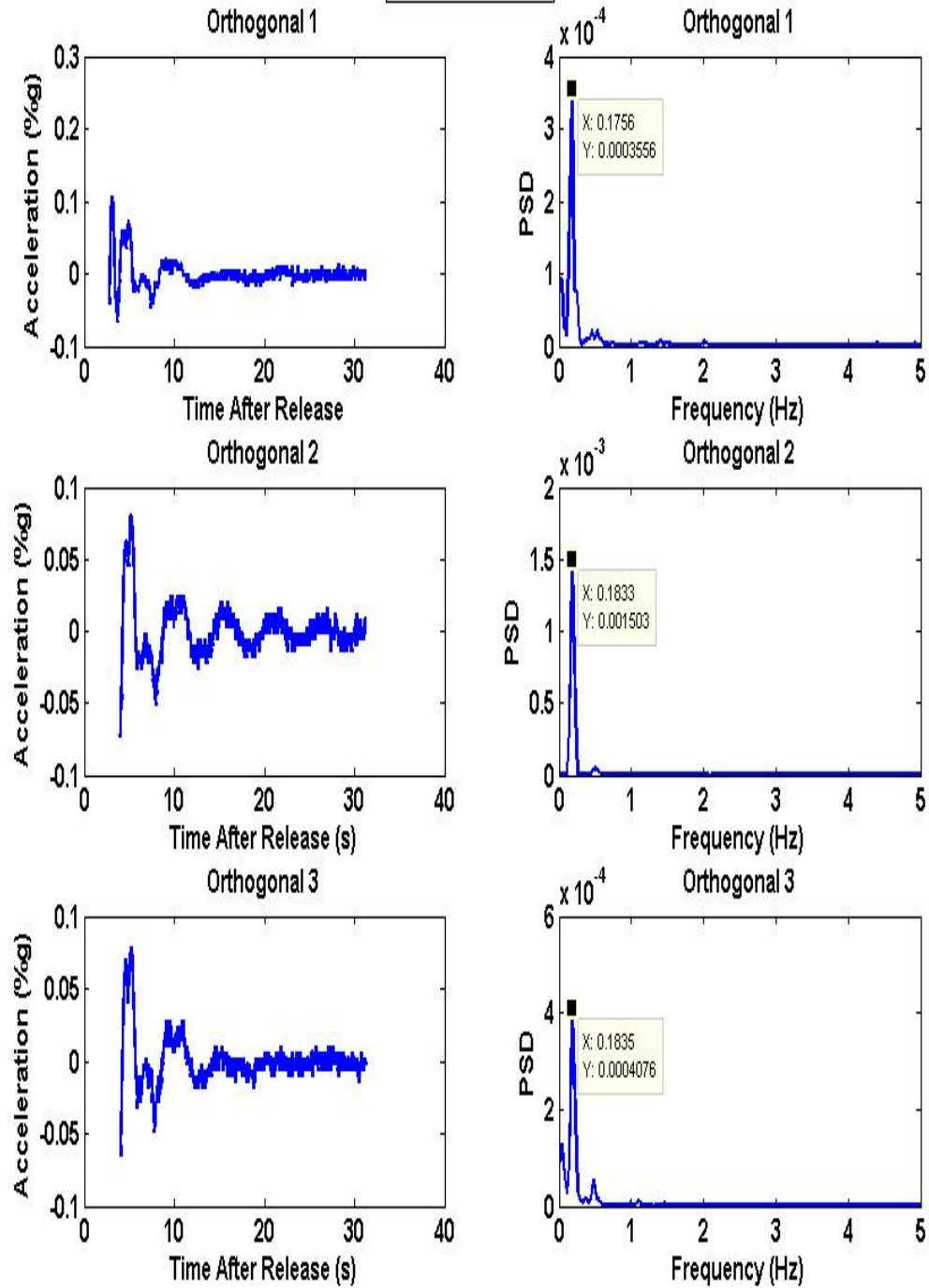
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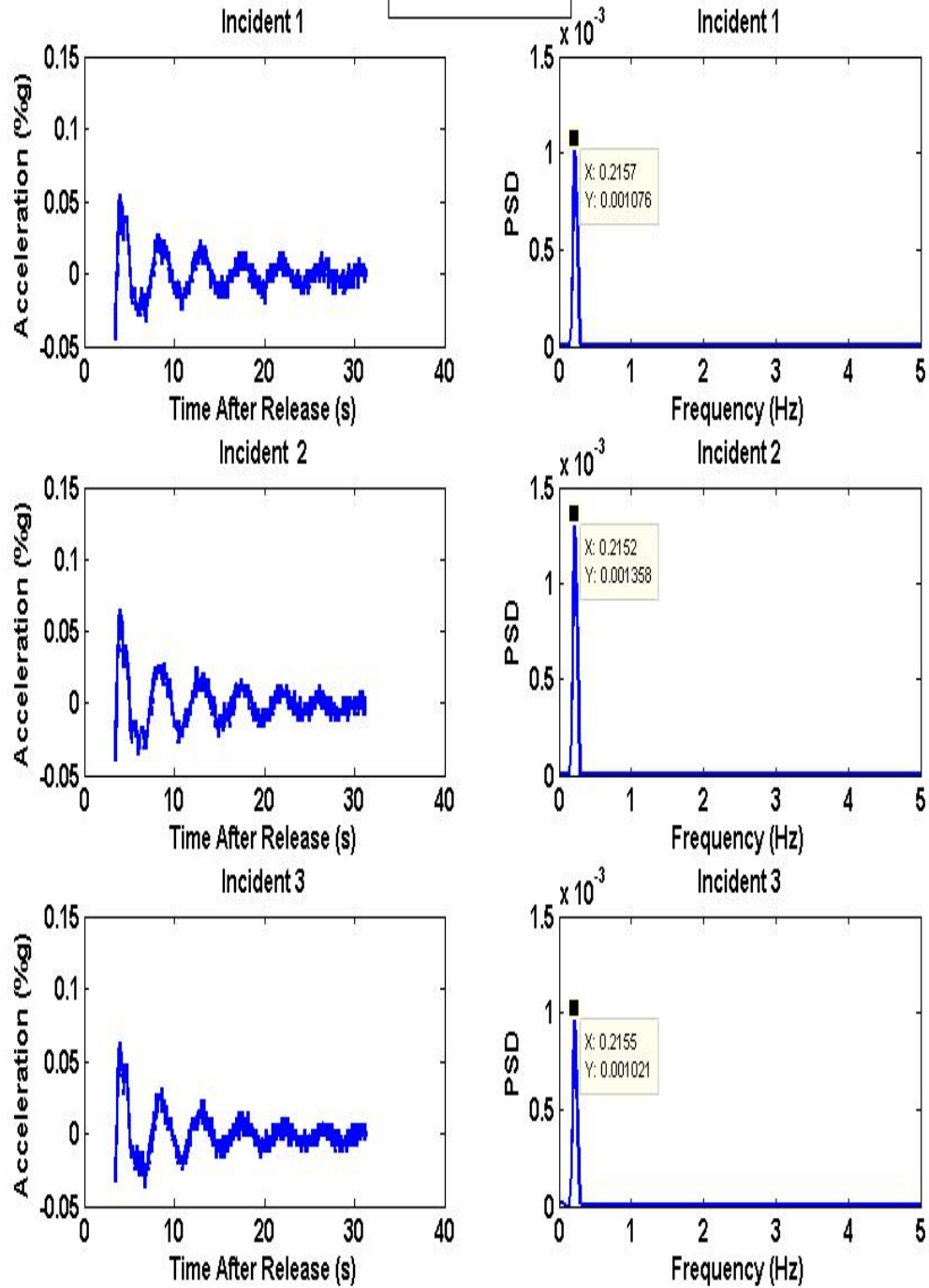
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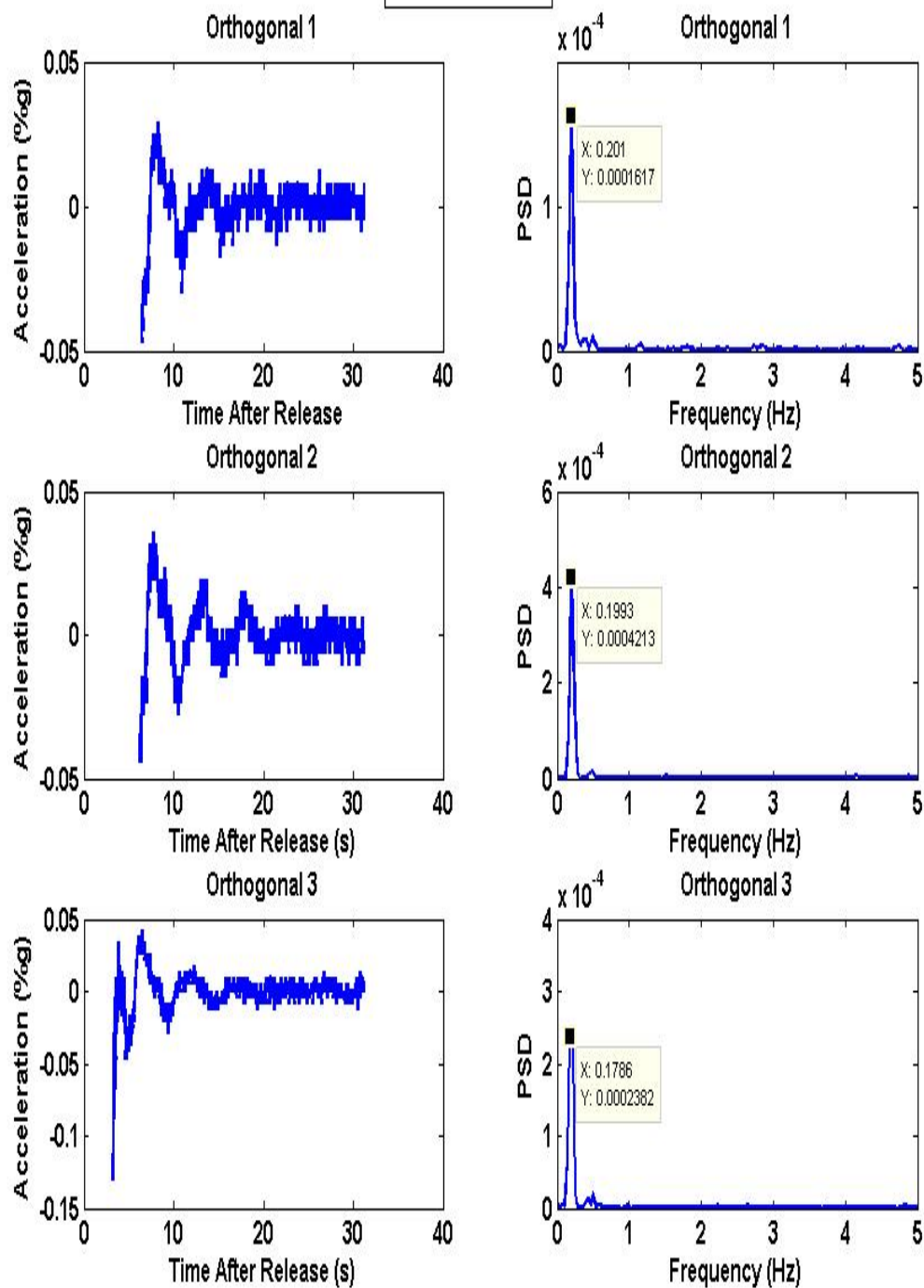
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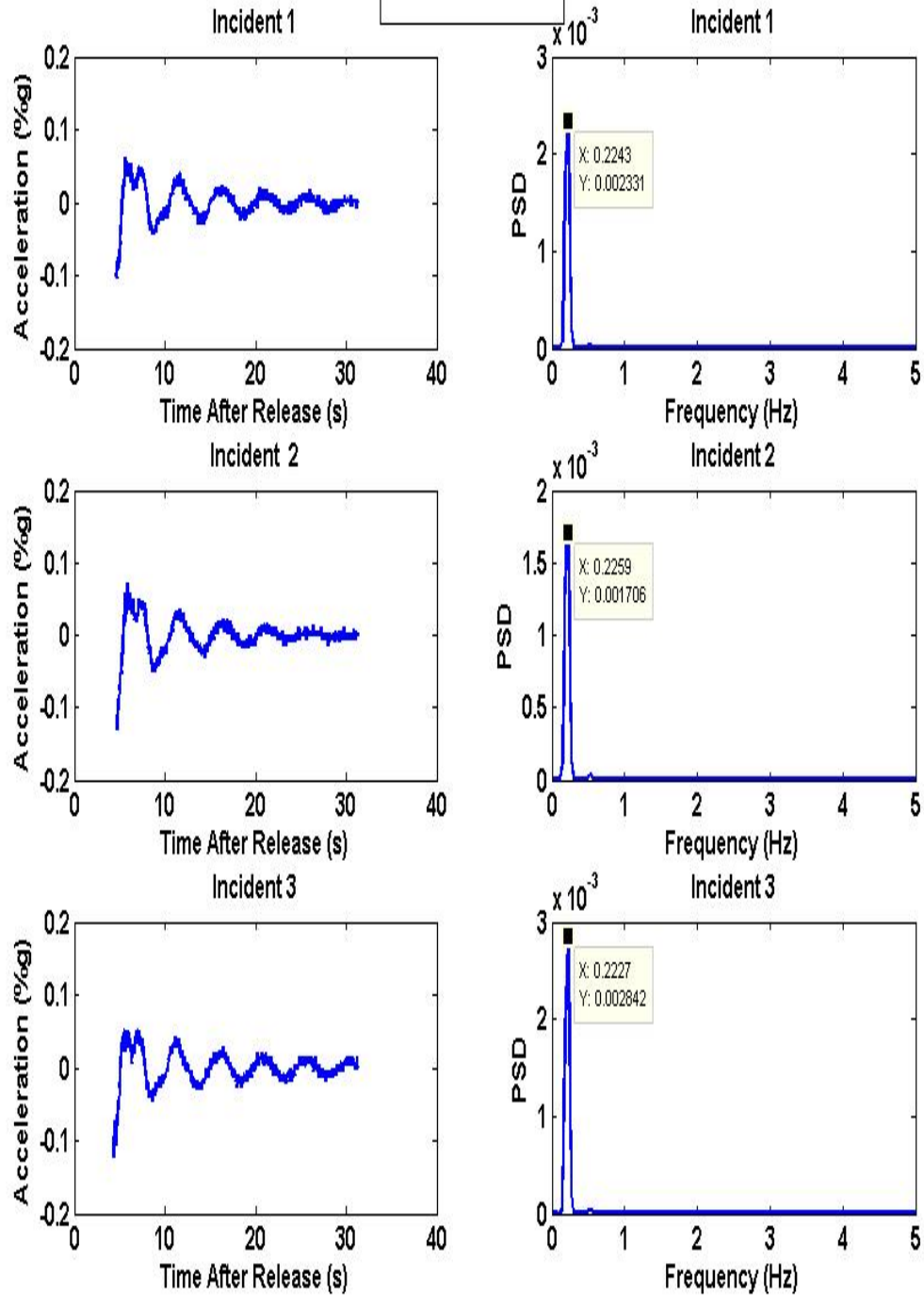
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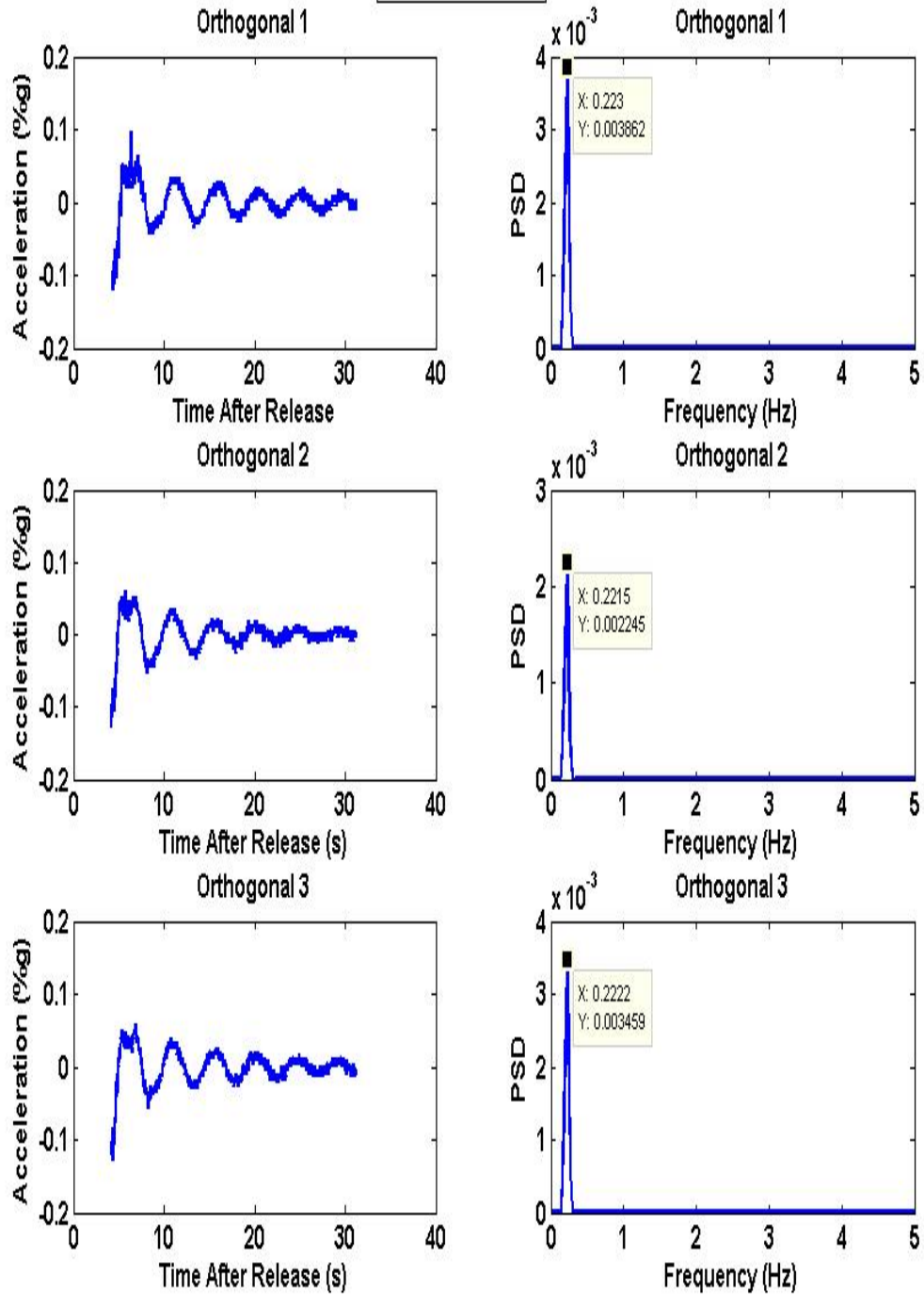
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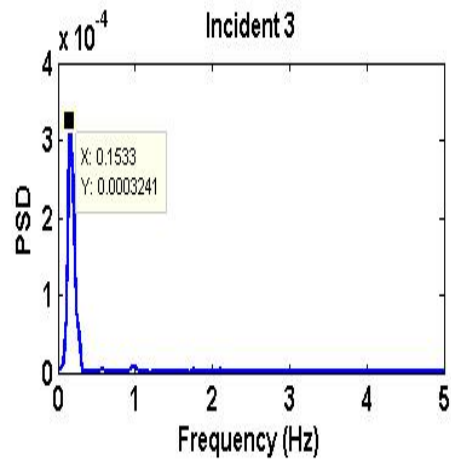
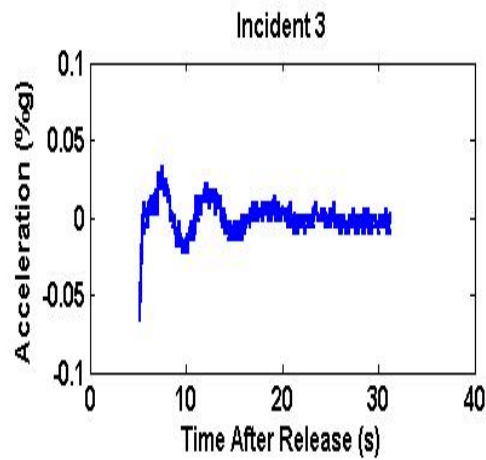
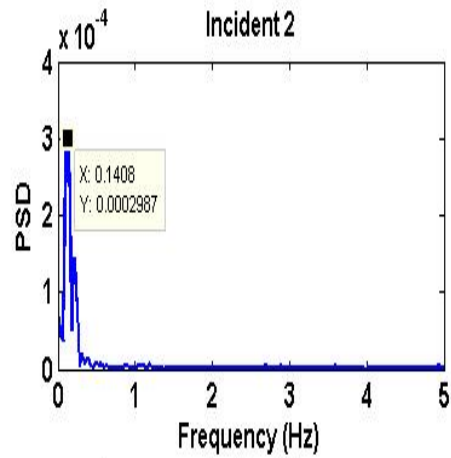
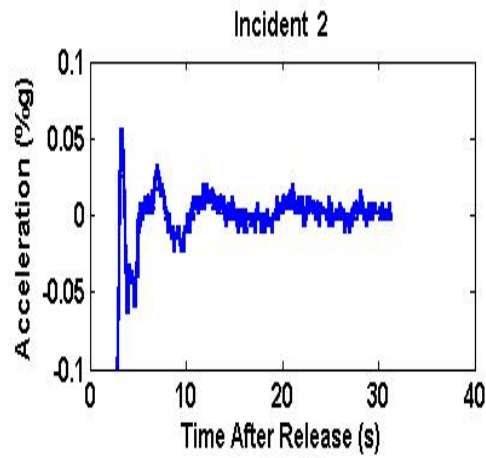
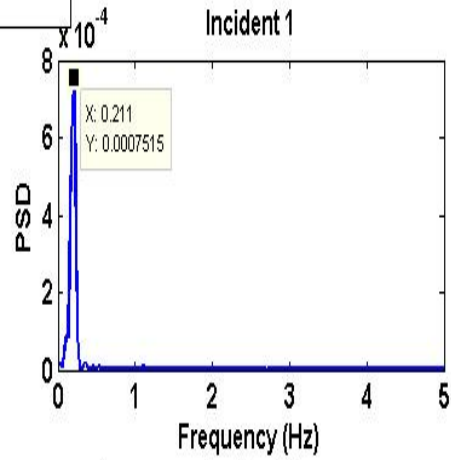
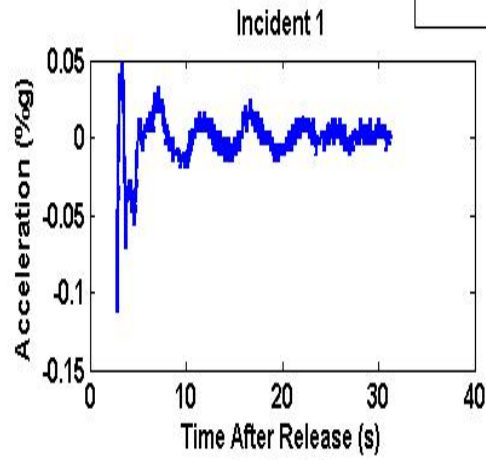
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Tree 55 Leaf On

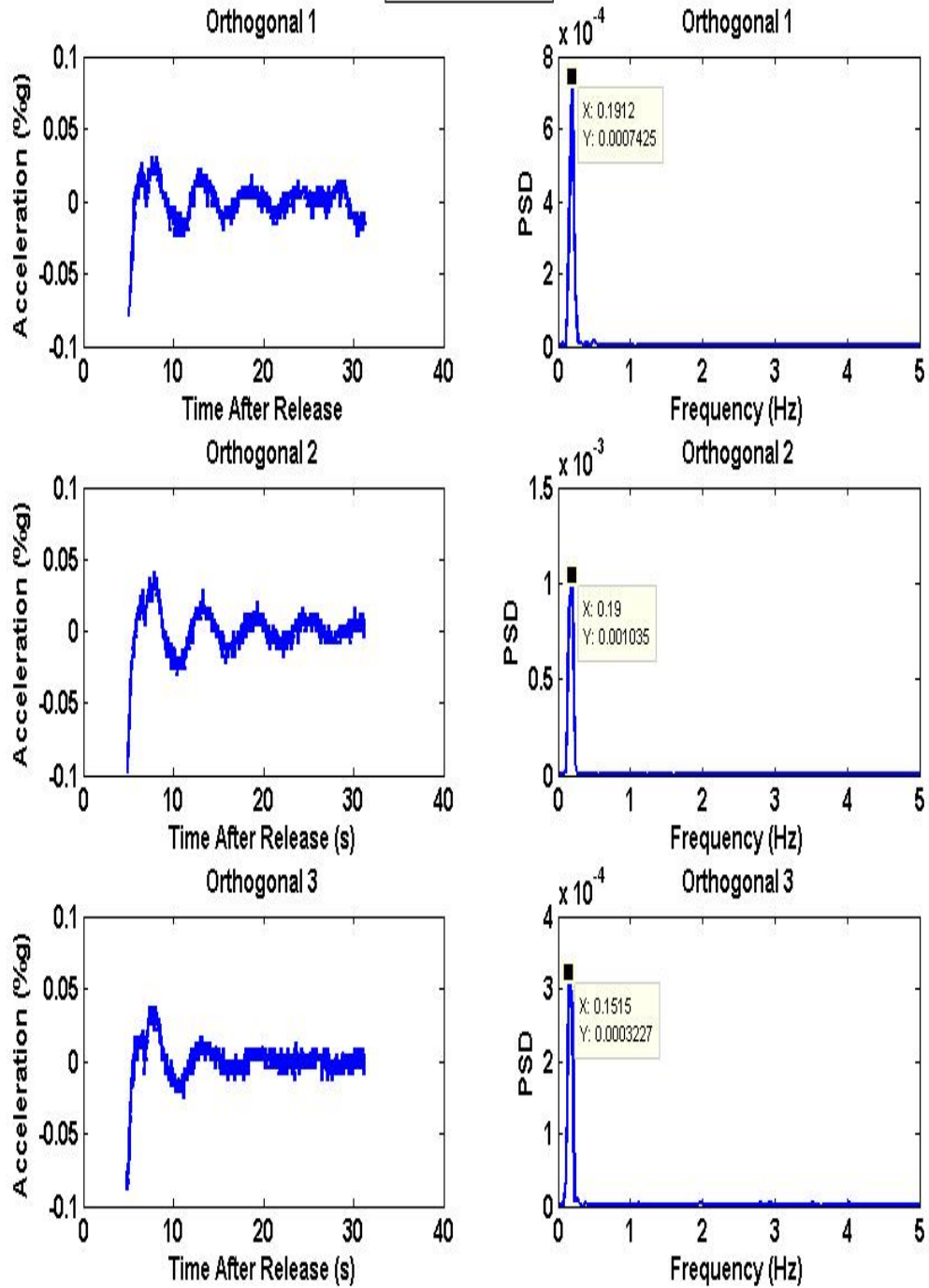


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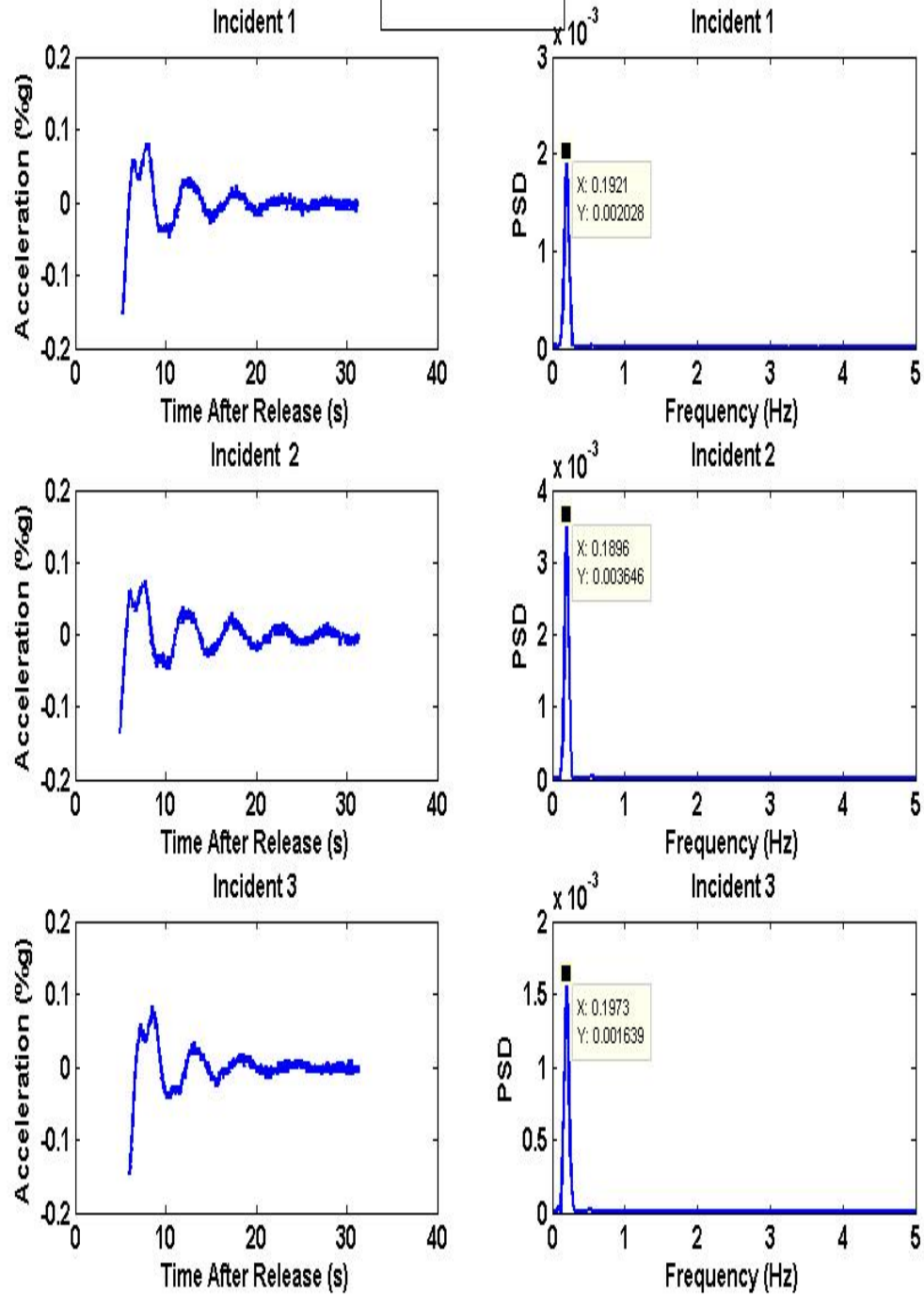




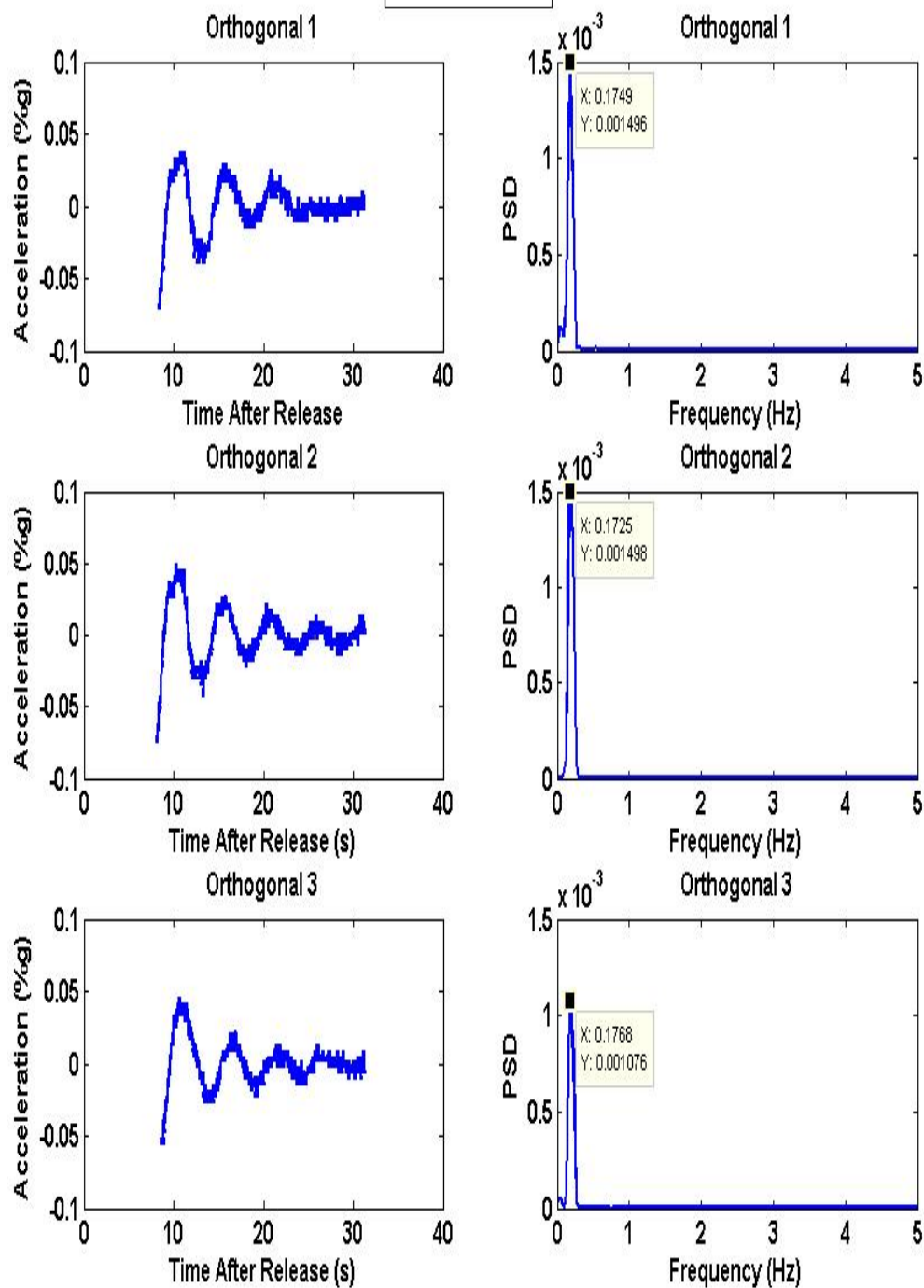
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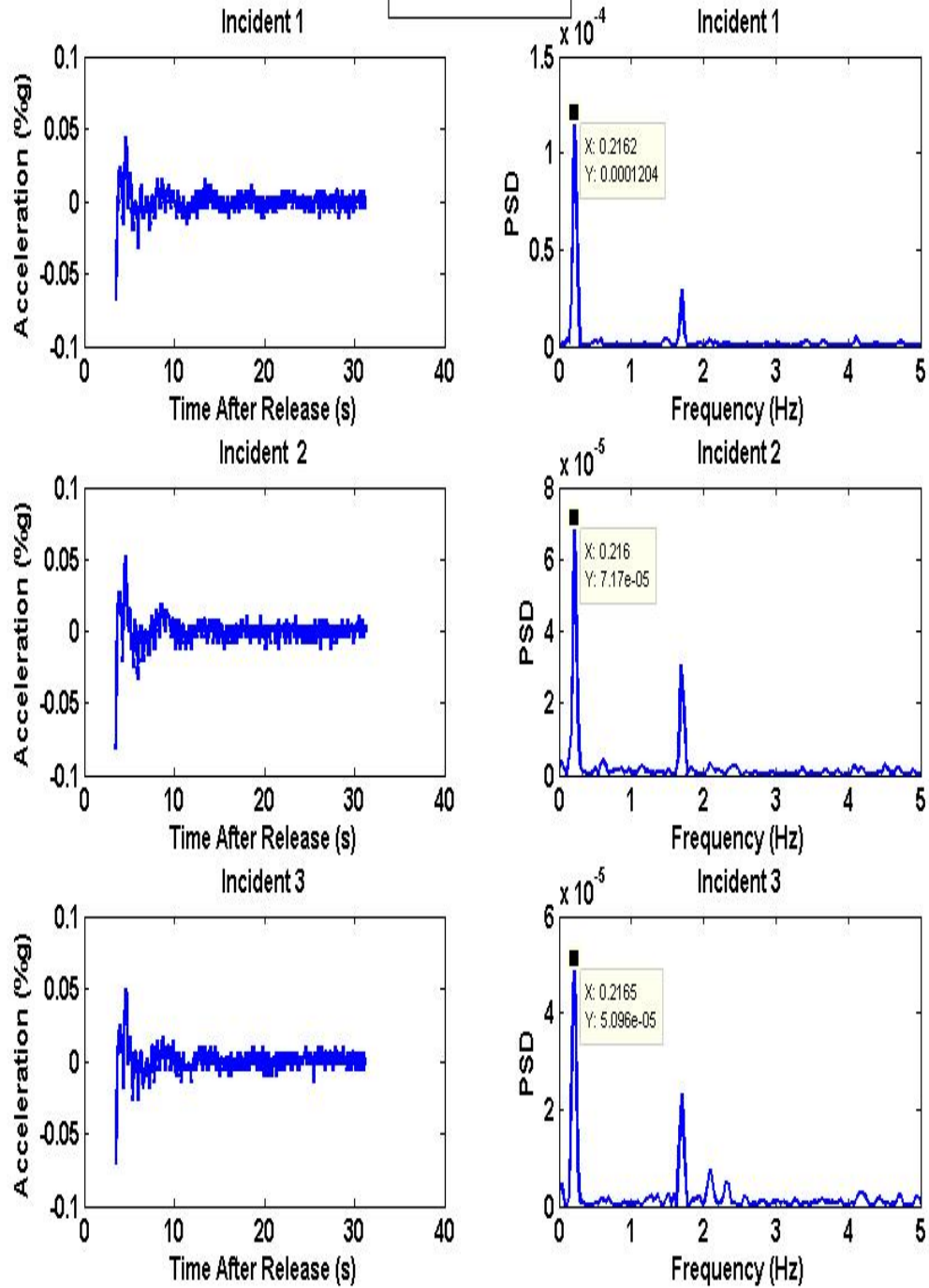
Tree 58 Leaf On



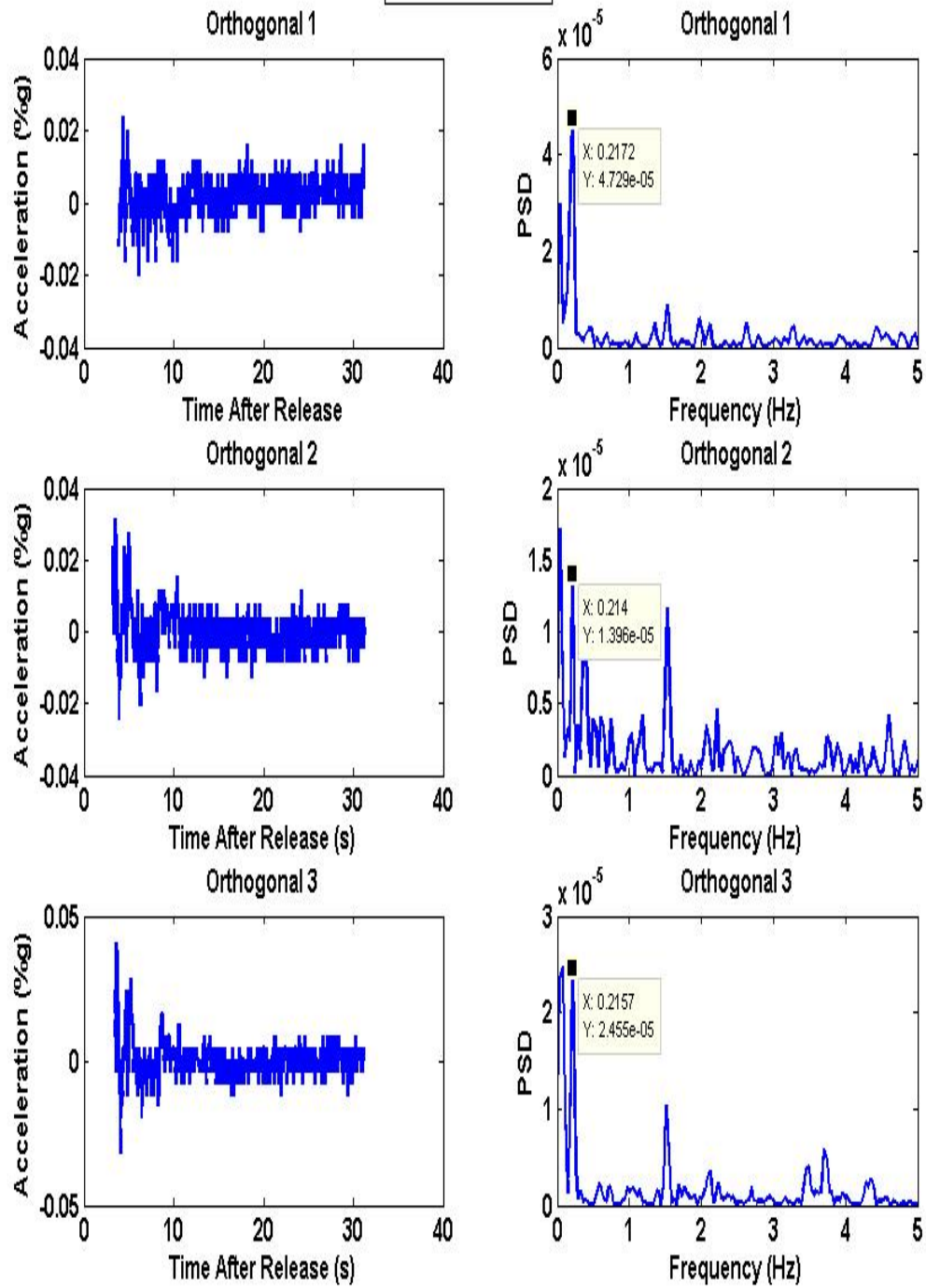
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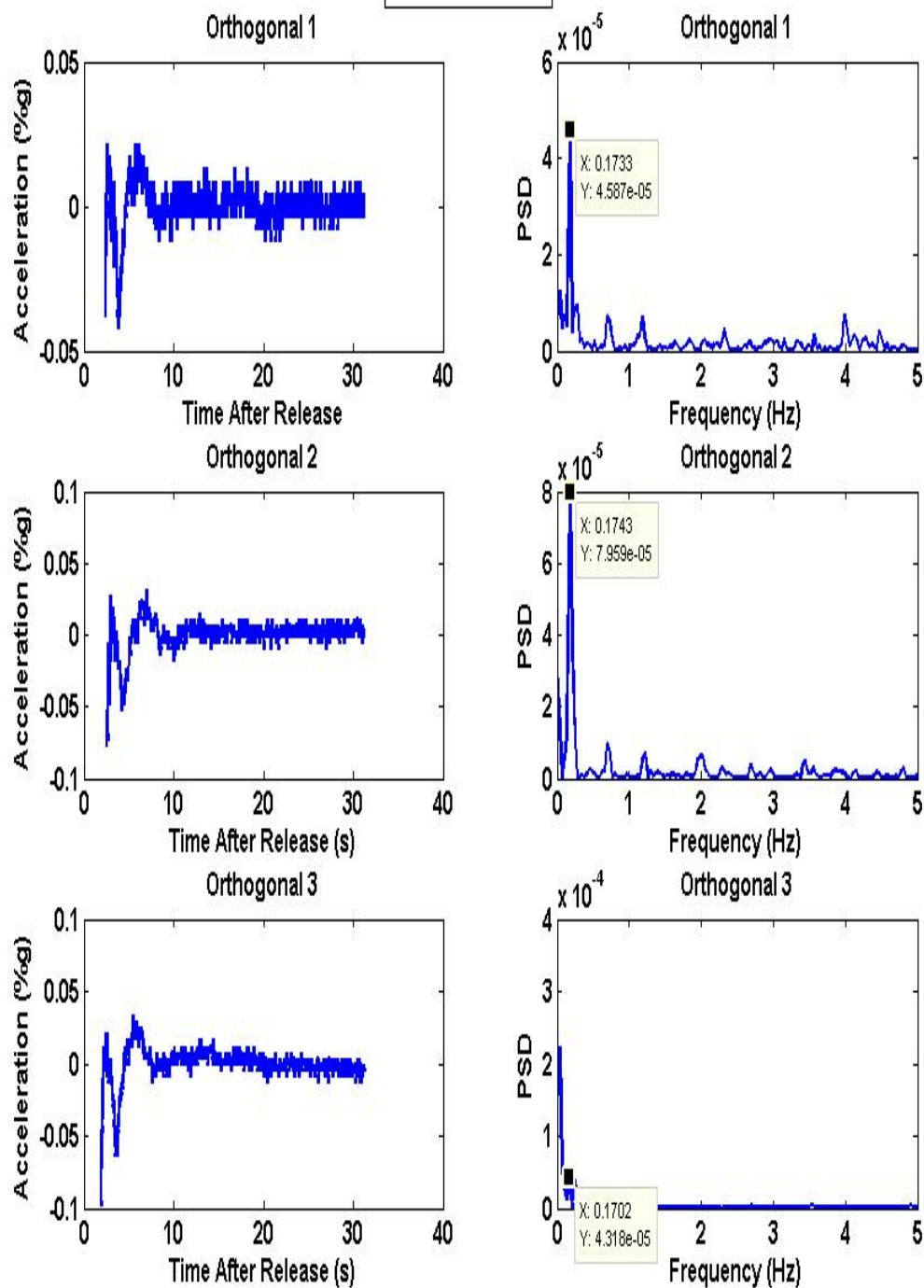
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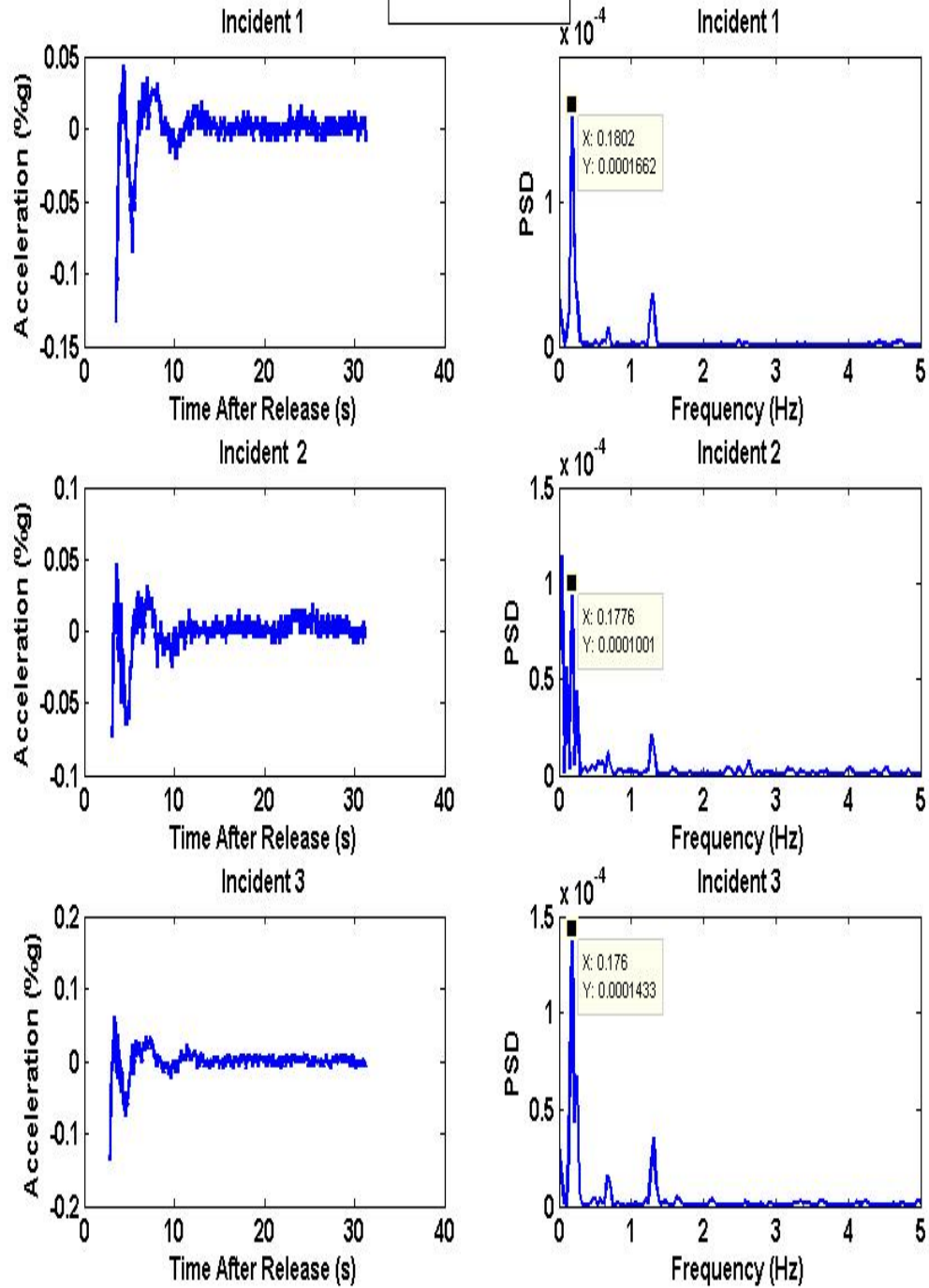
Tree 59 Leaf On



Tree 61 Leaf On



# Tree 61 Leaf On



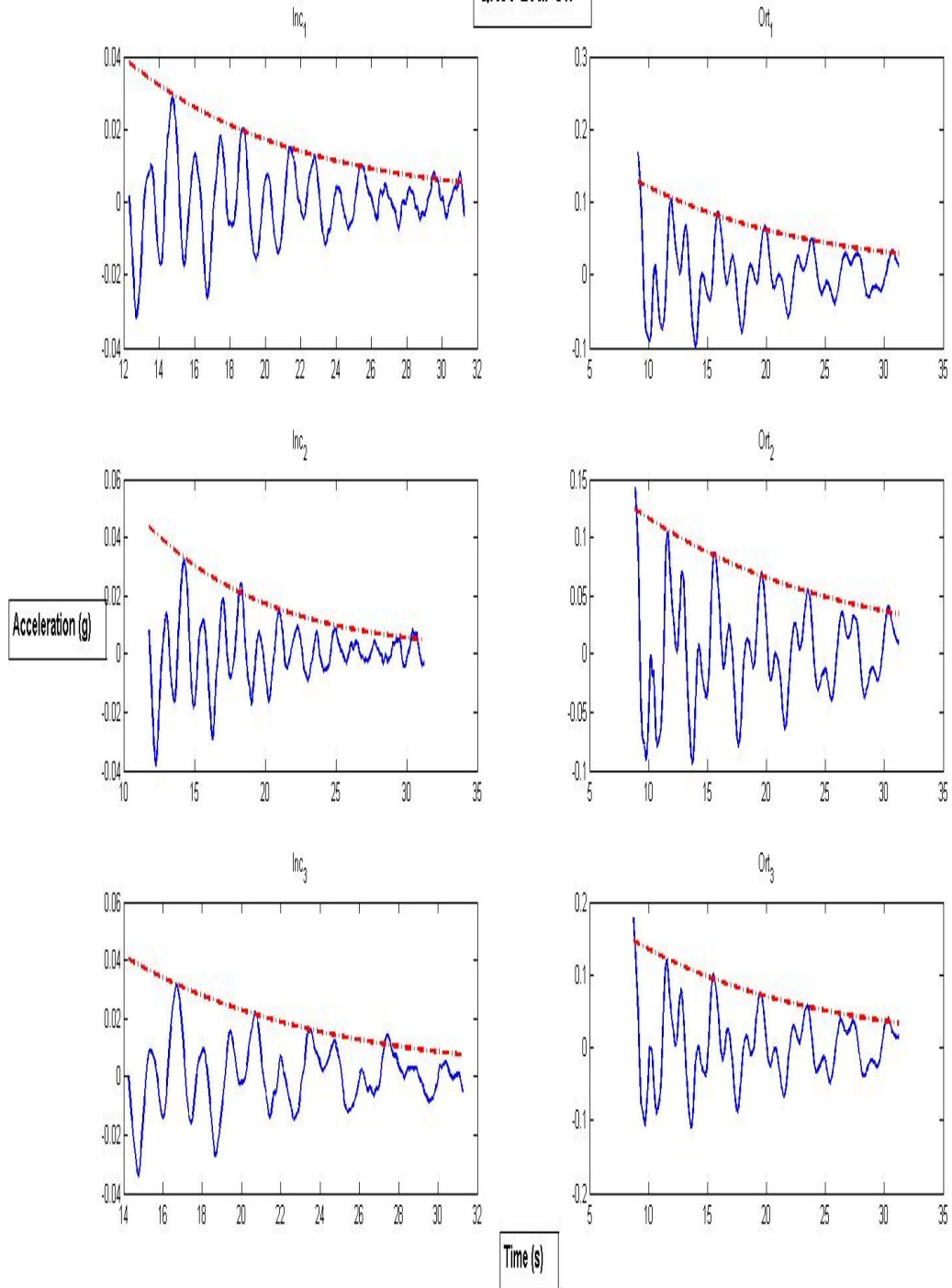
## **APPENDIX B**

### **ACCELERATION VS TIME HISTORIES WITH DECAYING EXPONENTIAL FUNCTION**

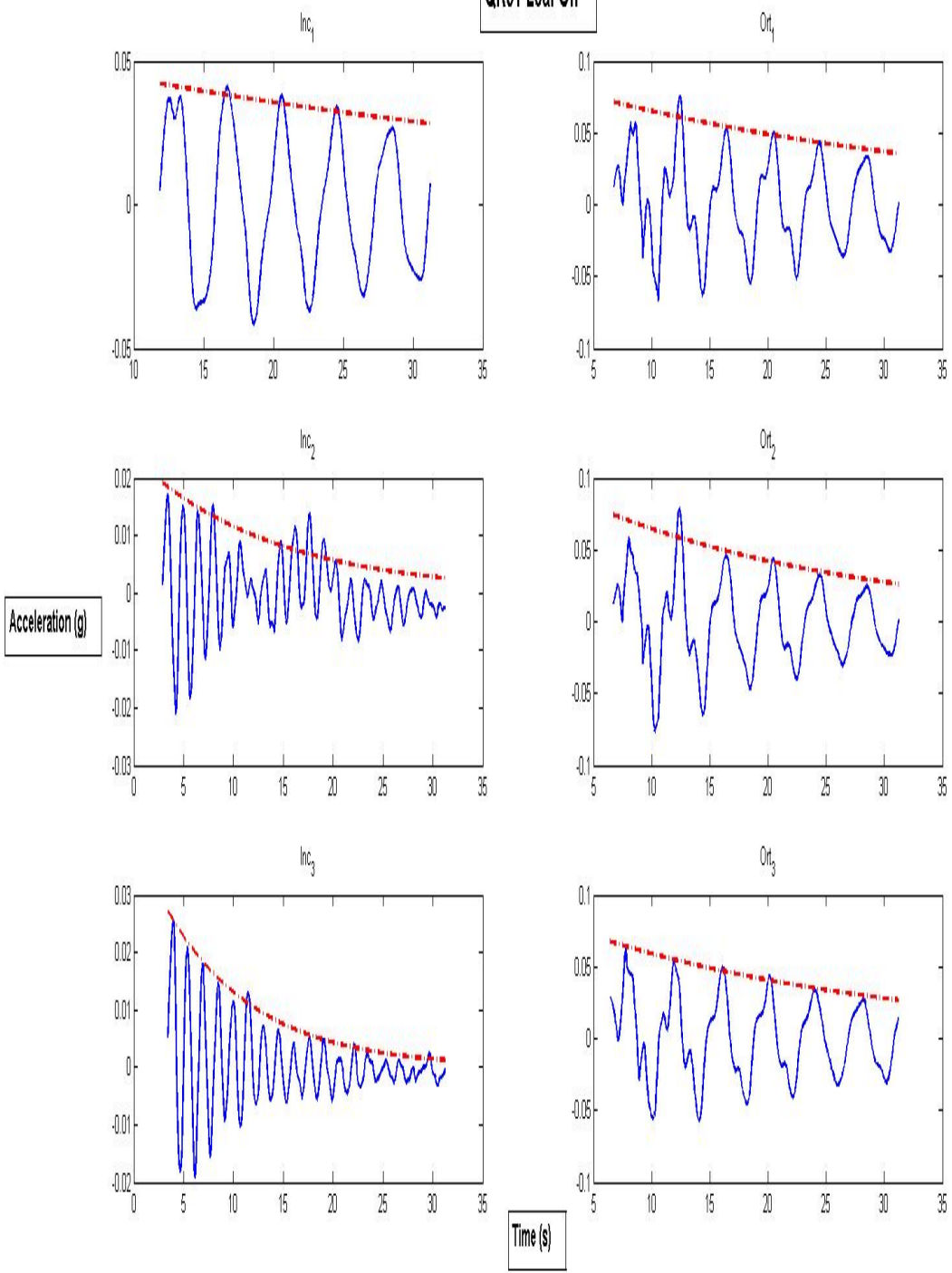


## Leaf Off

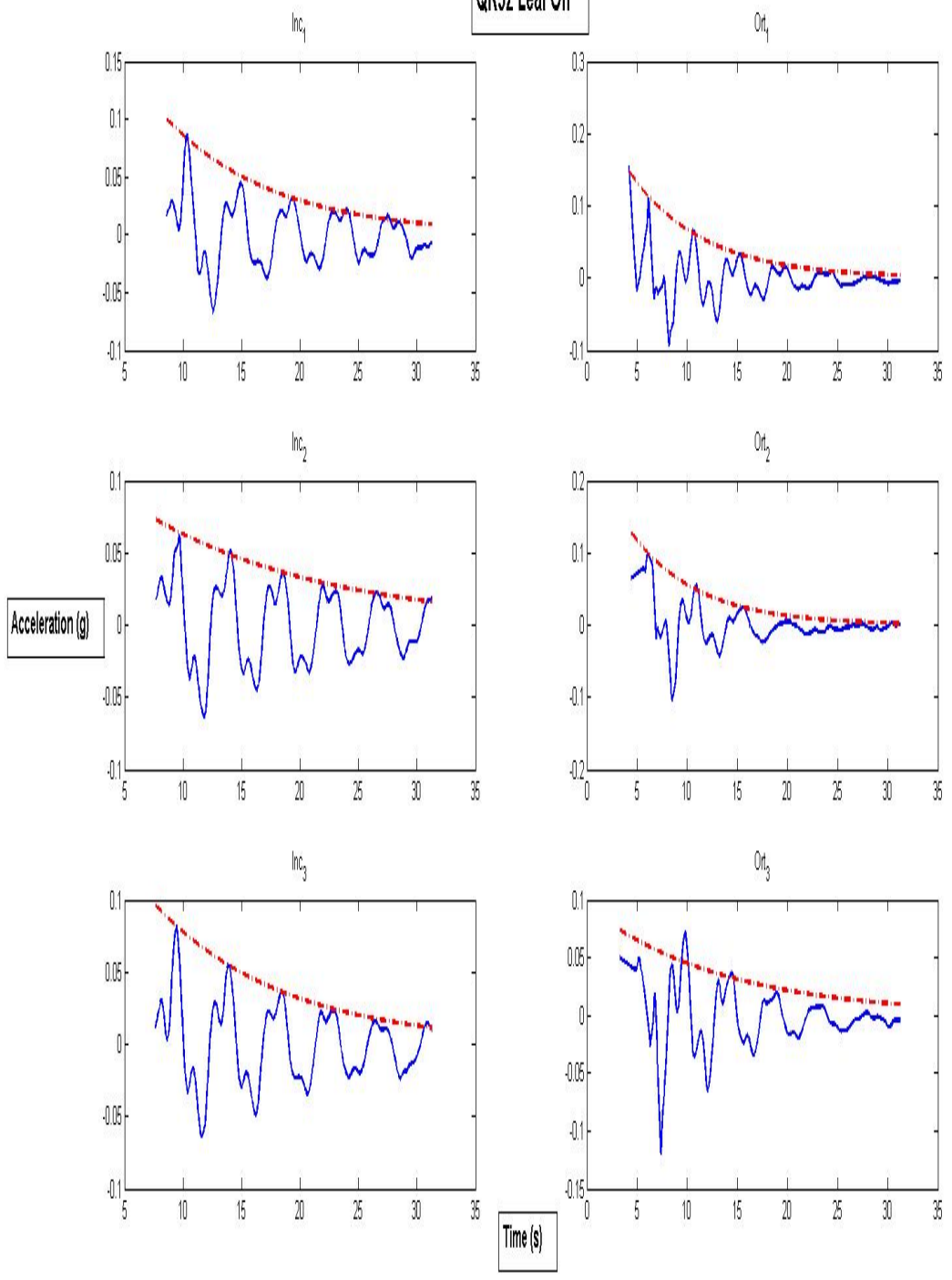
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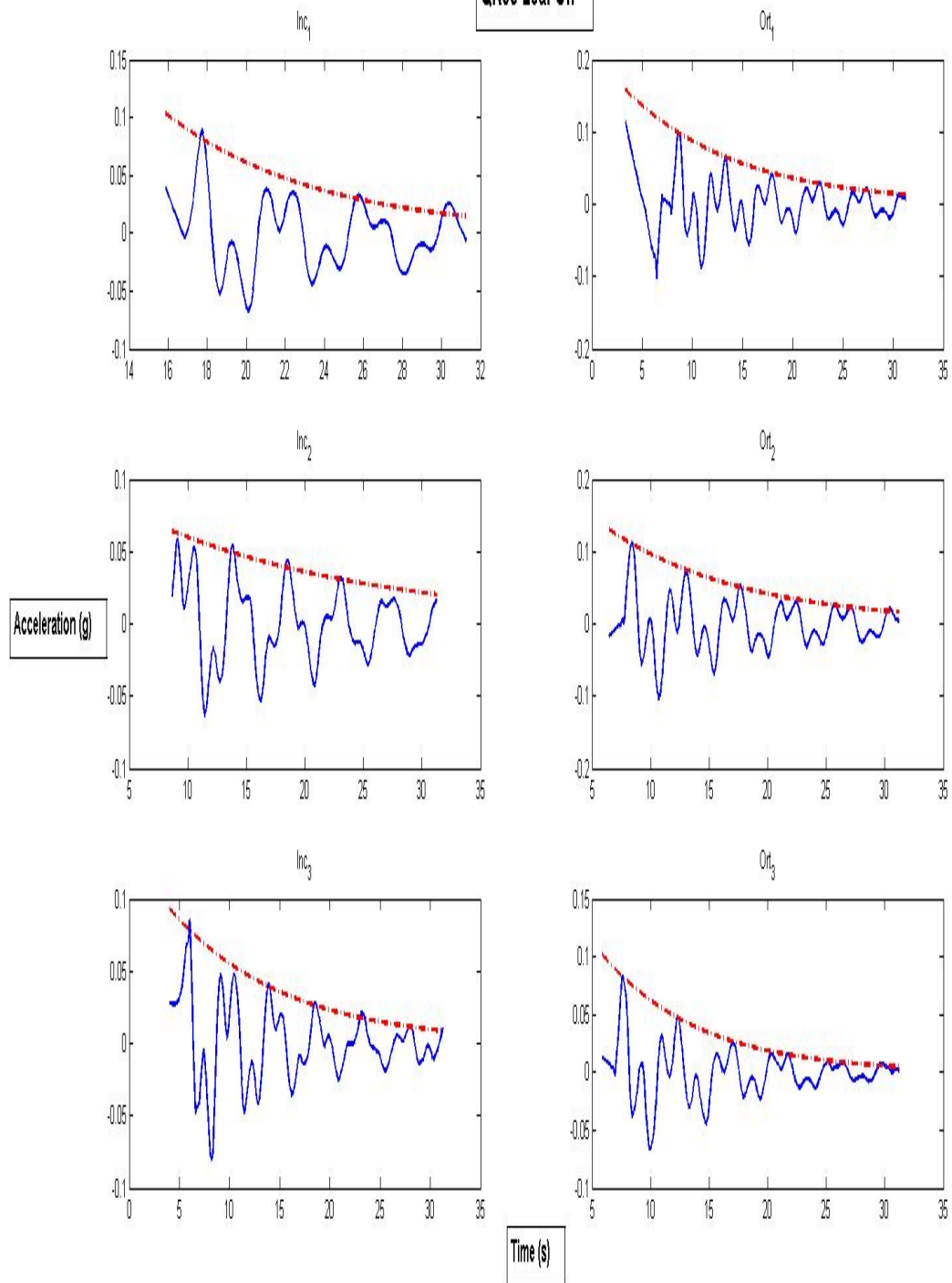
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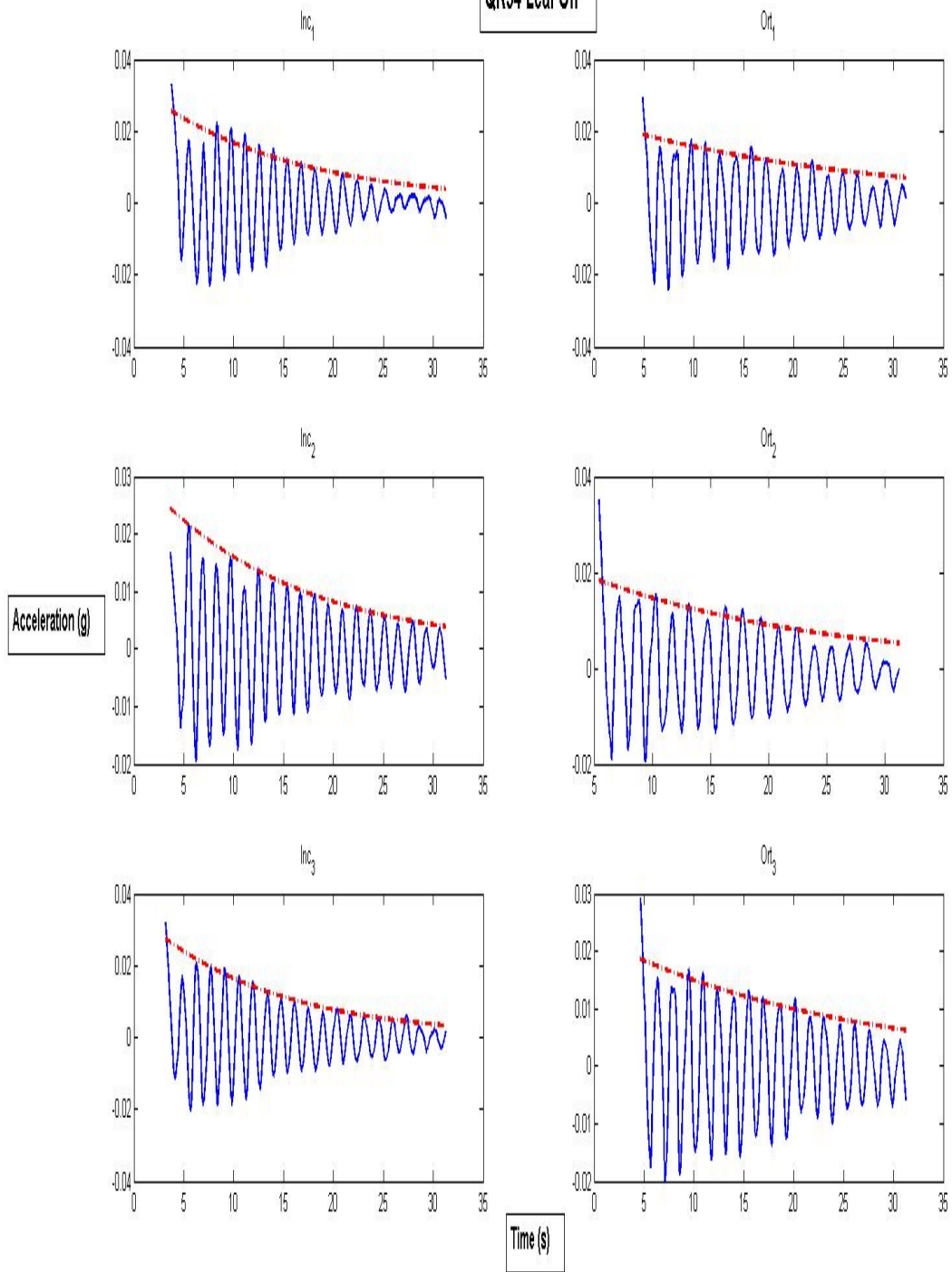
QR52 Leaf Off



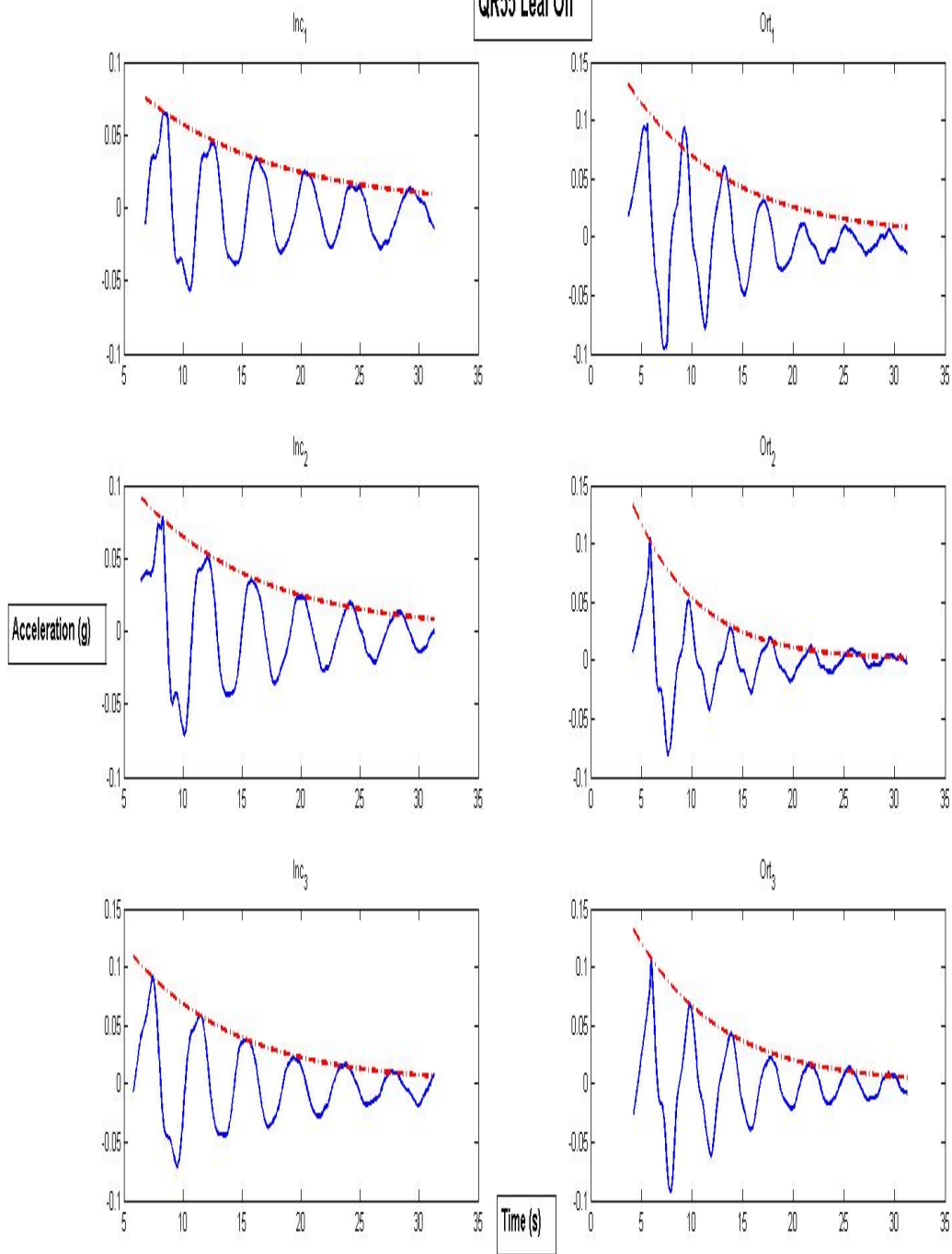
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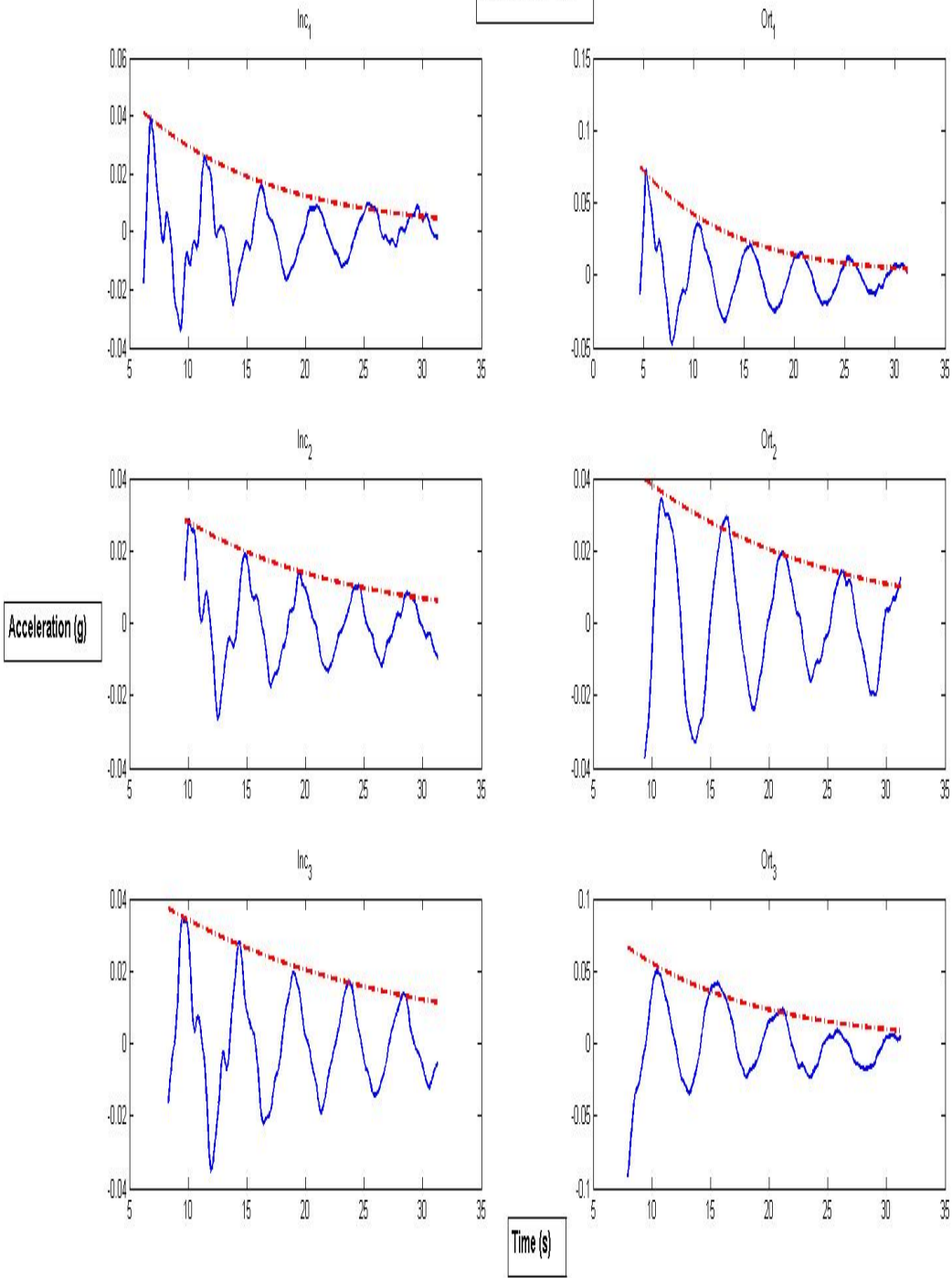
# QR54 Leaf Off



# QR55 Leaf Off

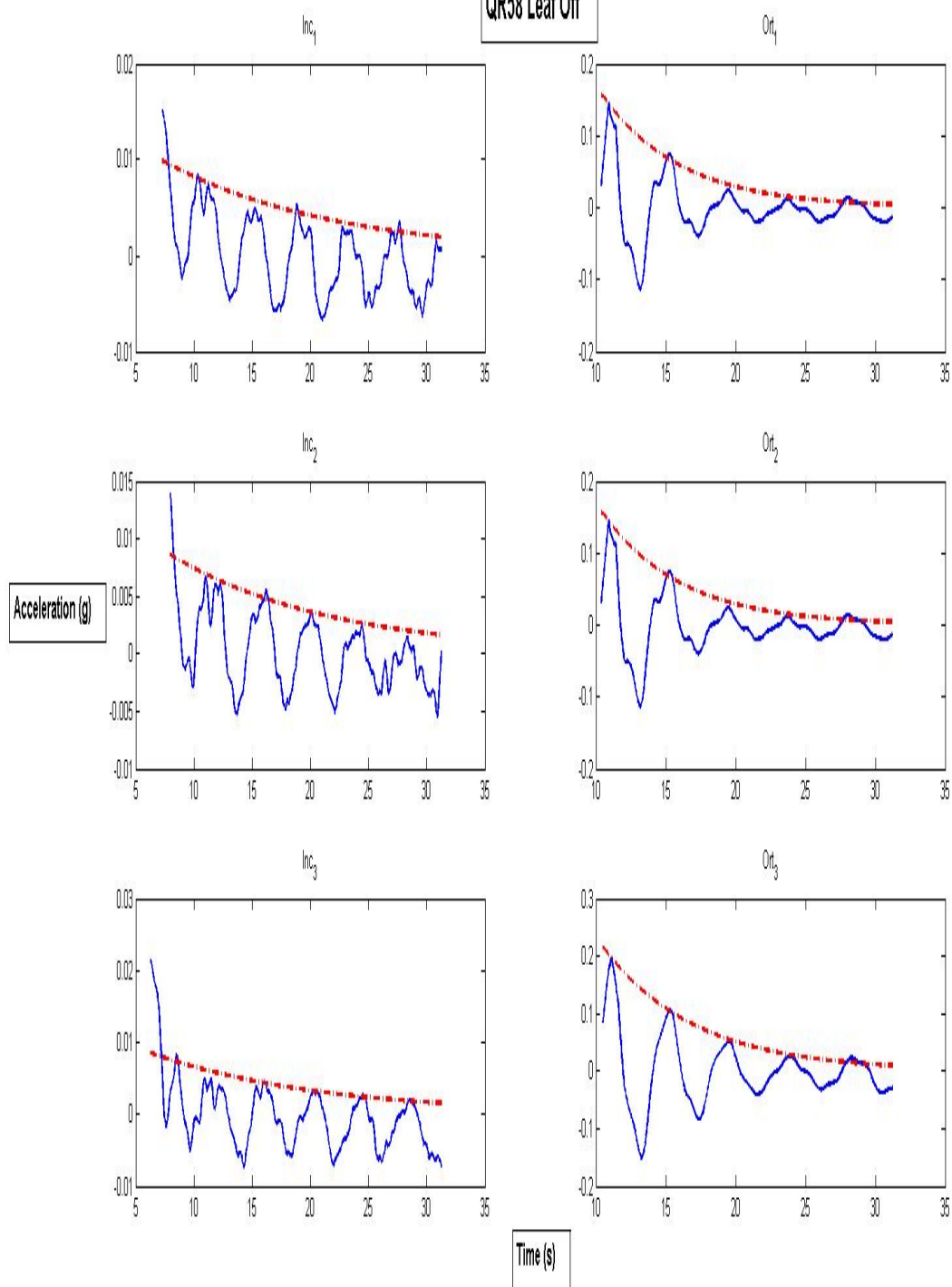


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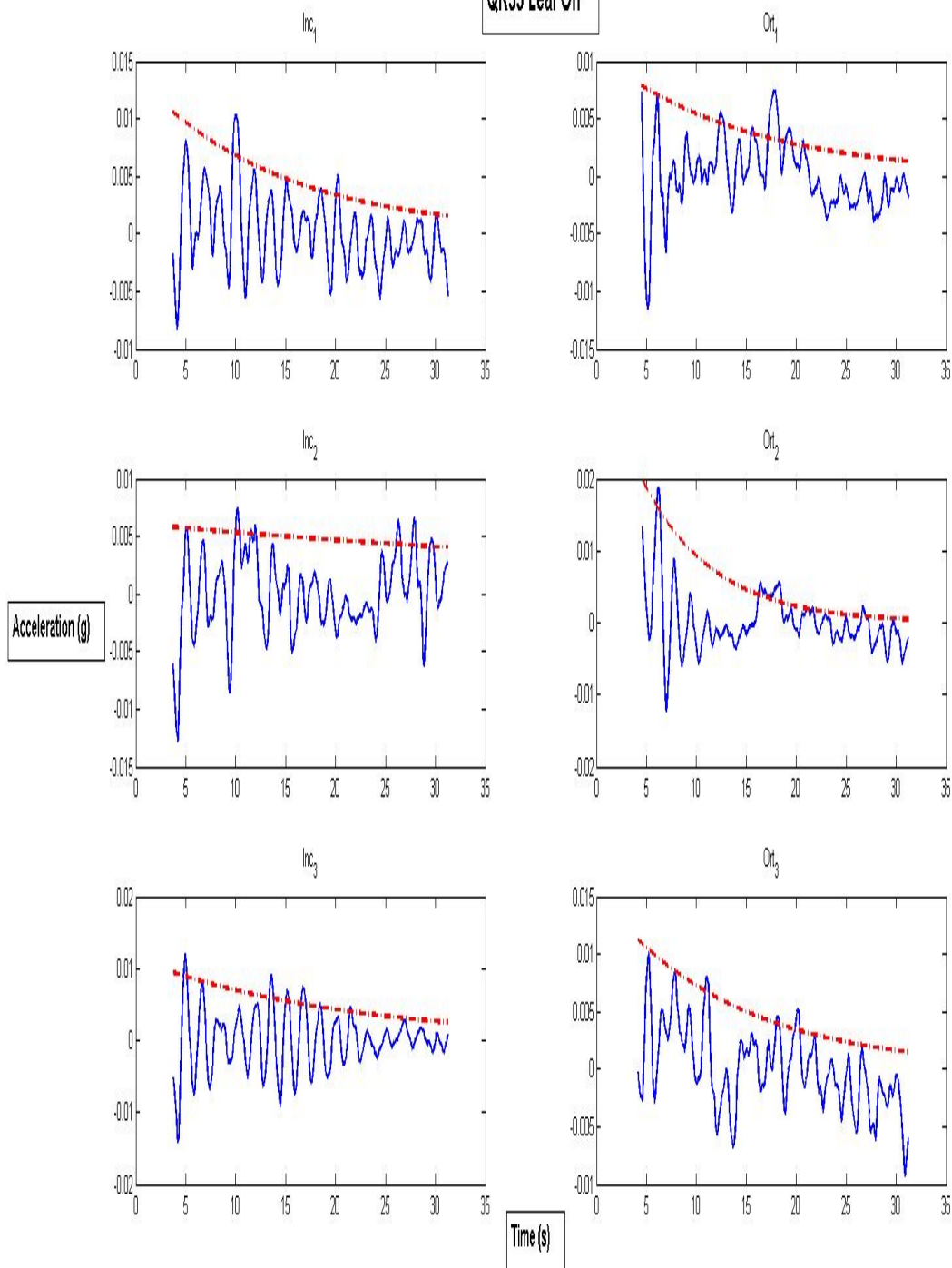


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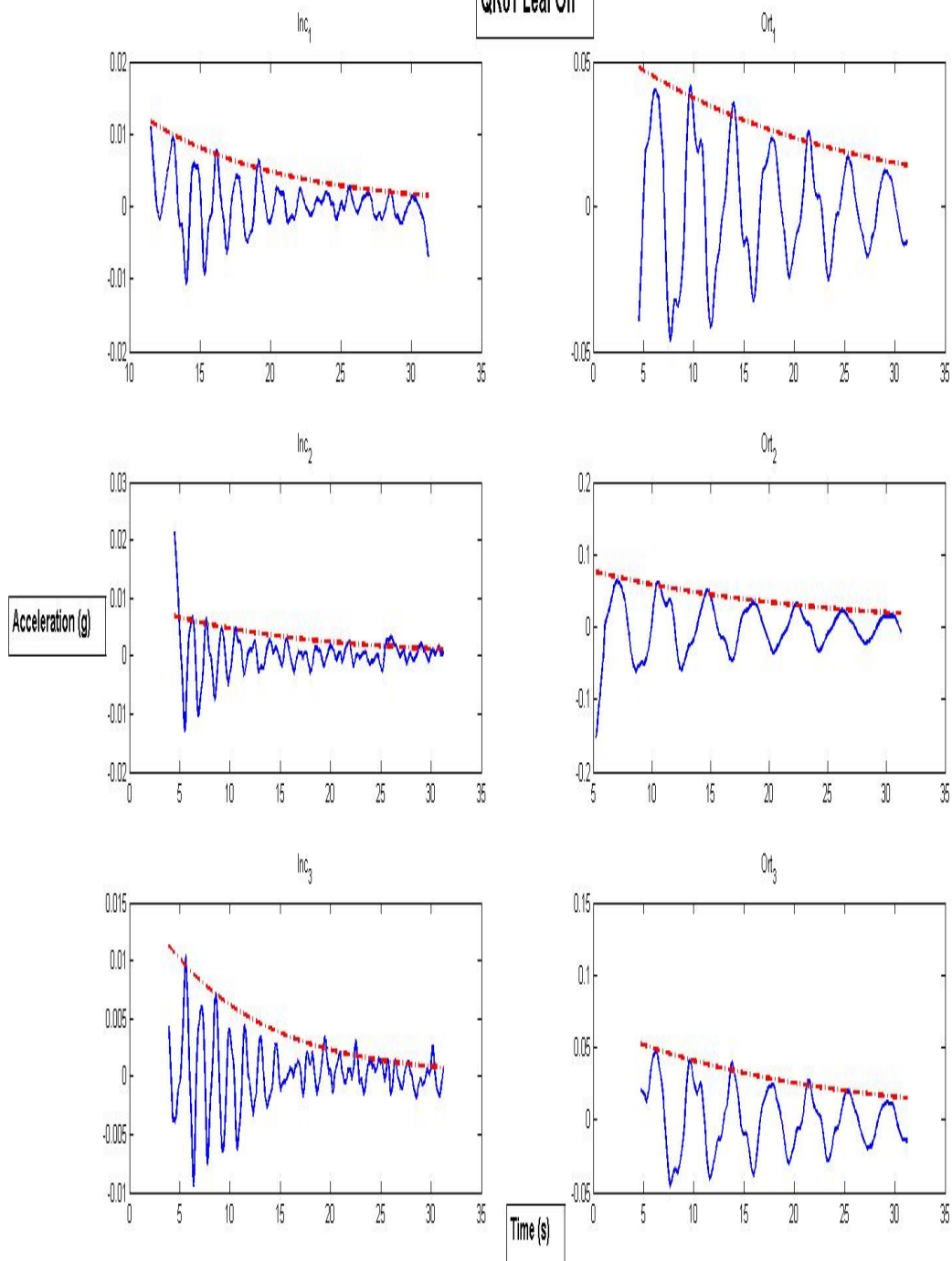




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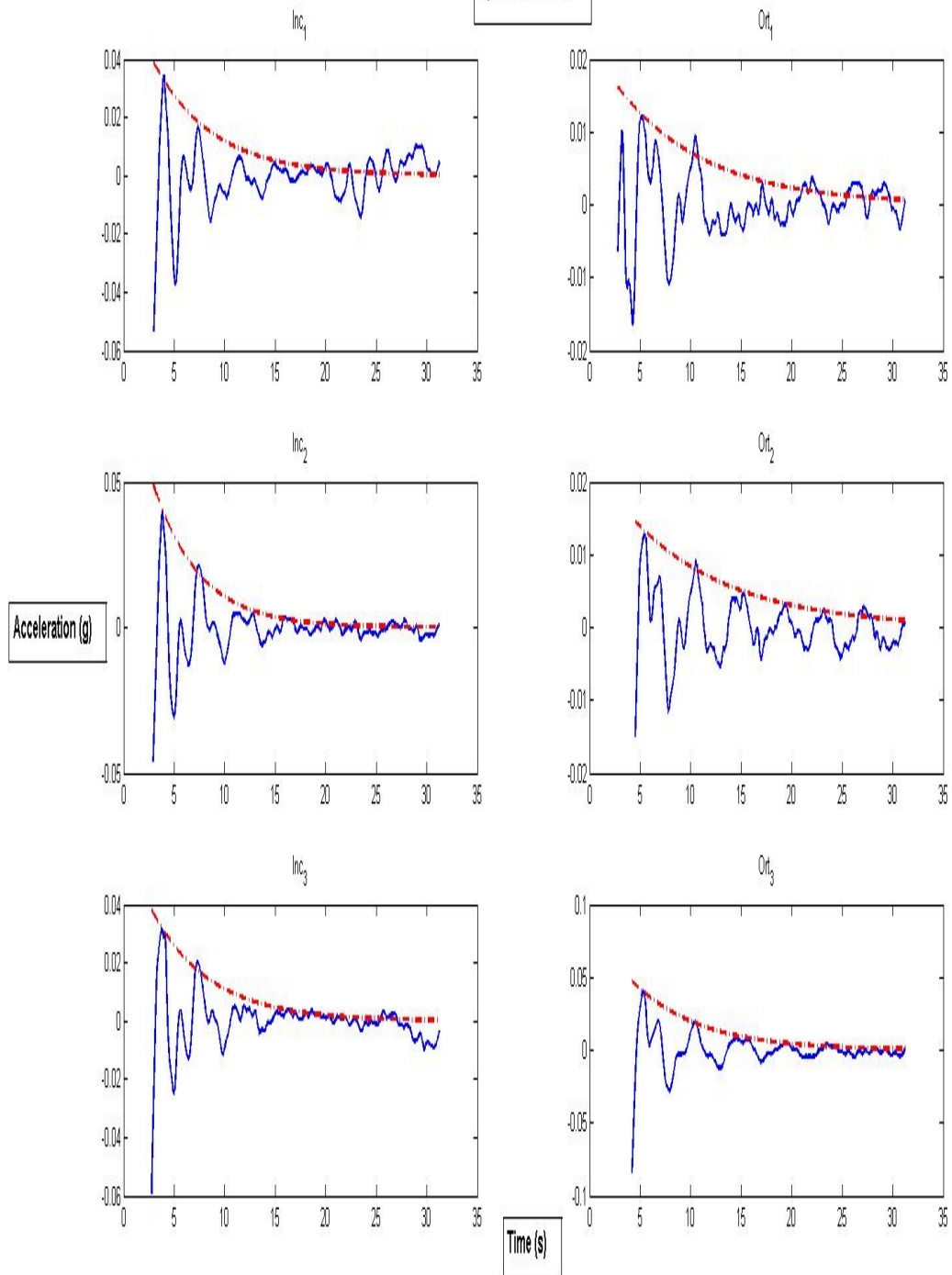


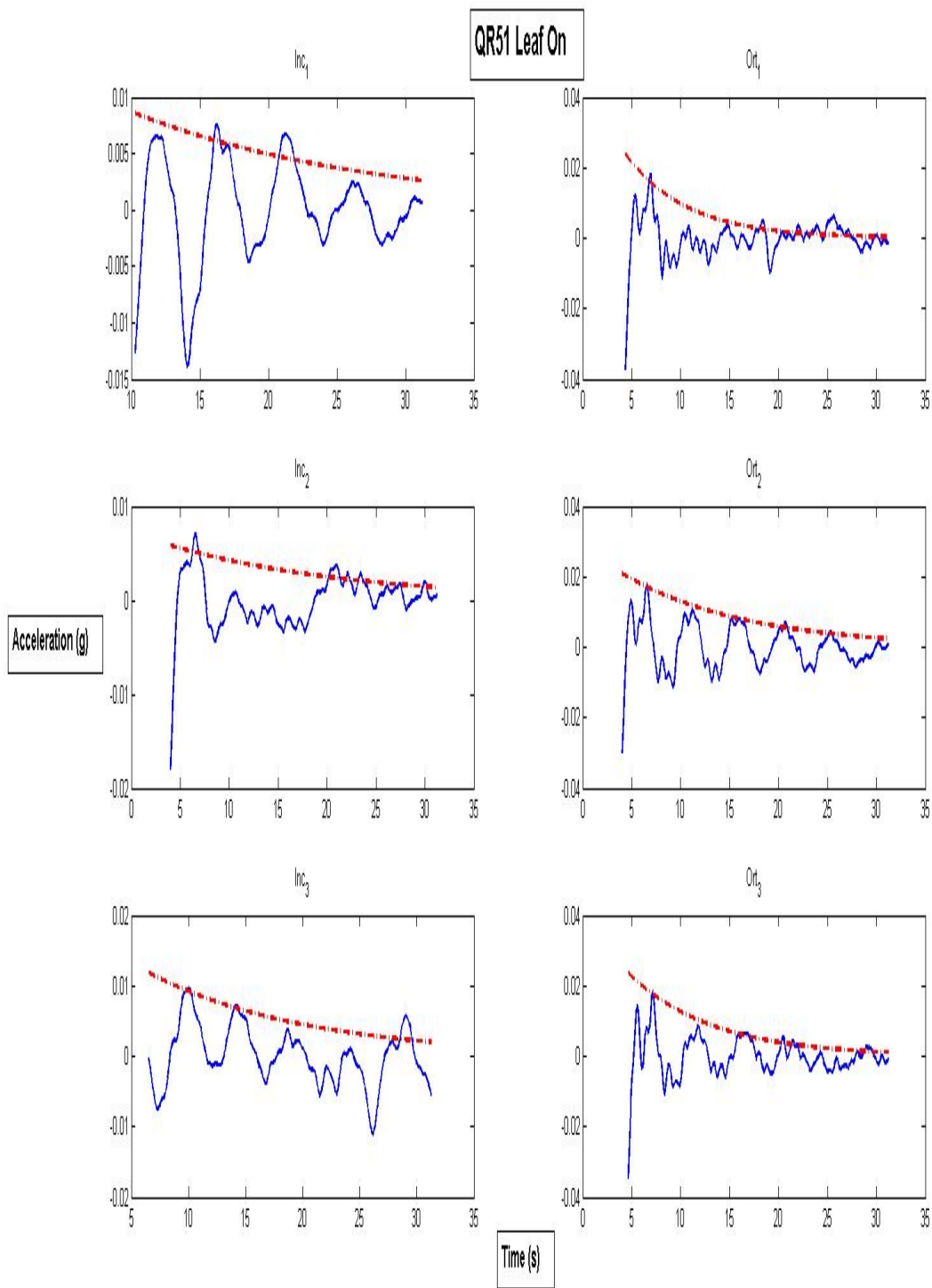
# QR61 Leaf Off



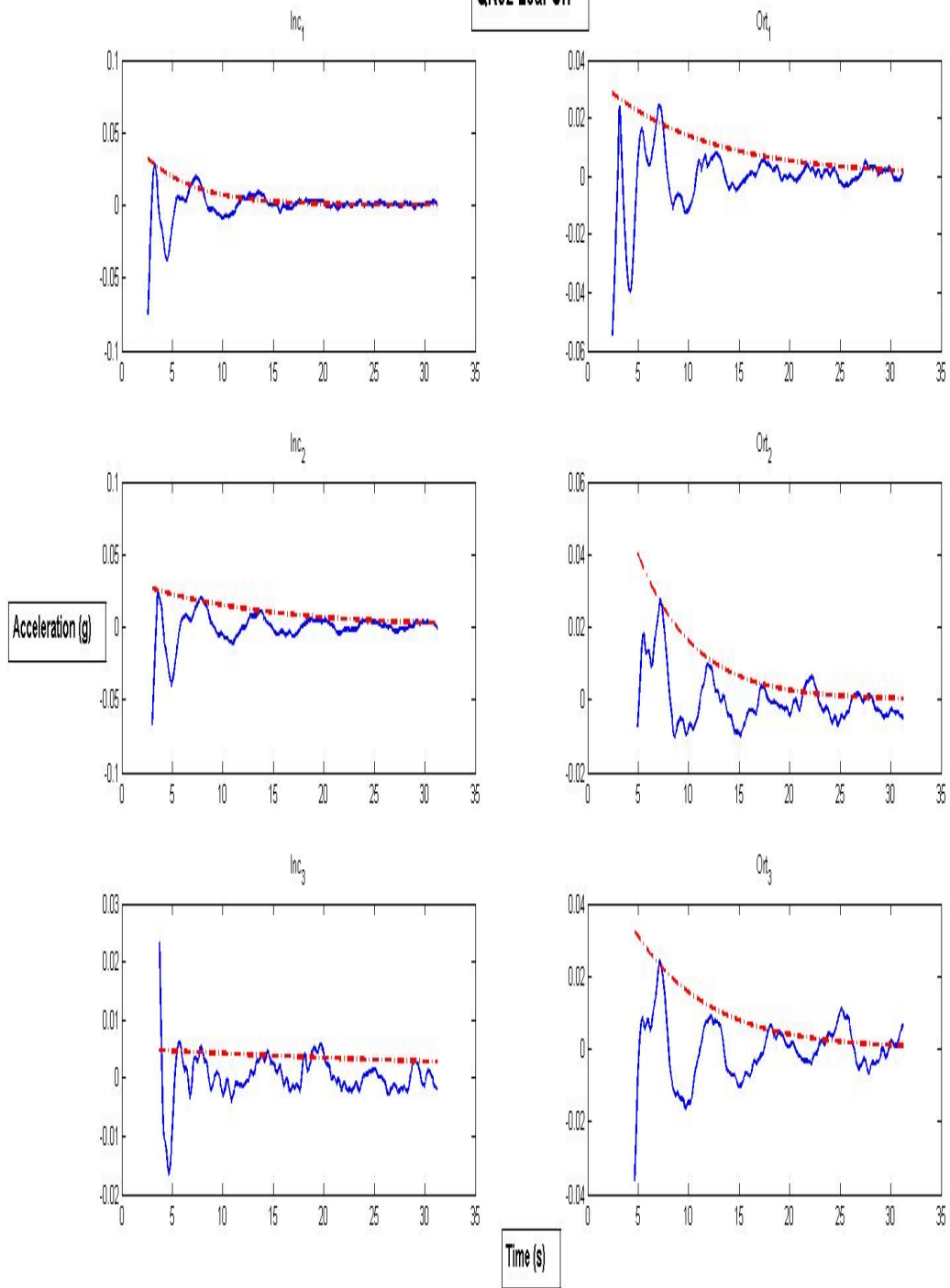
## Leaf On

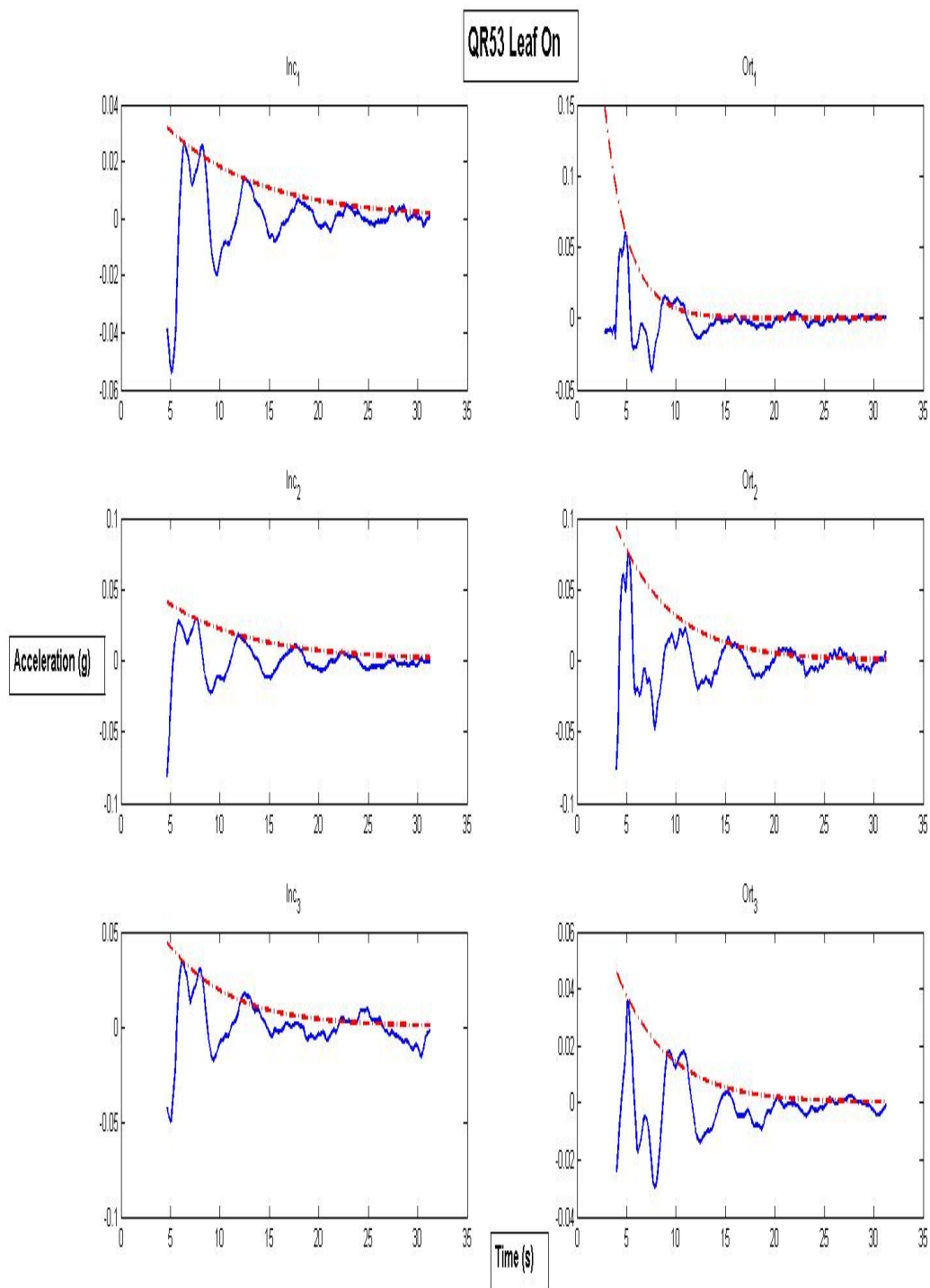
QR50 Leaf On

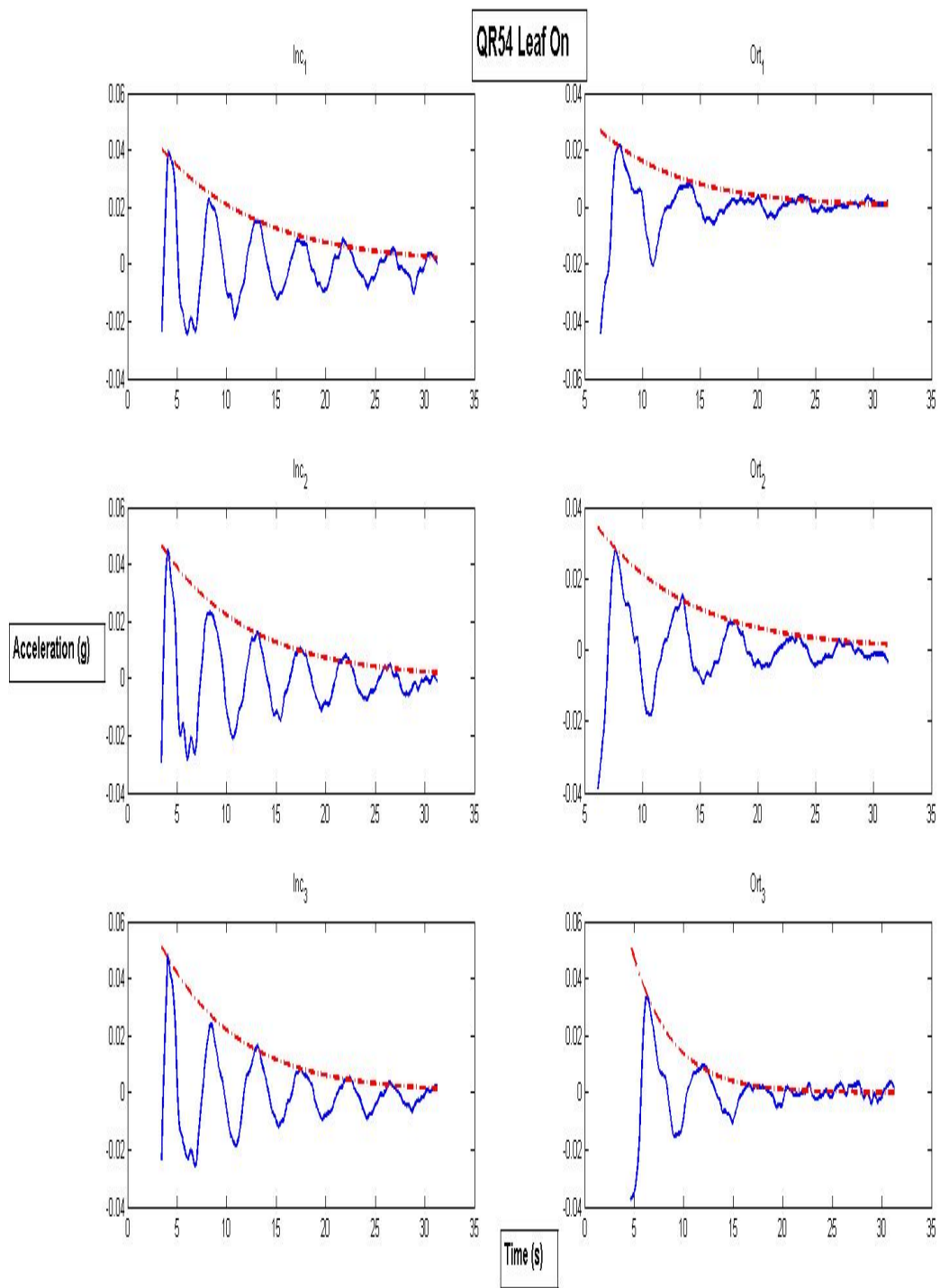




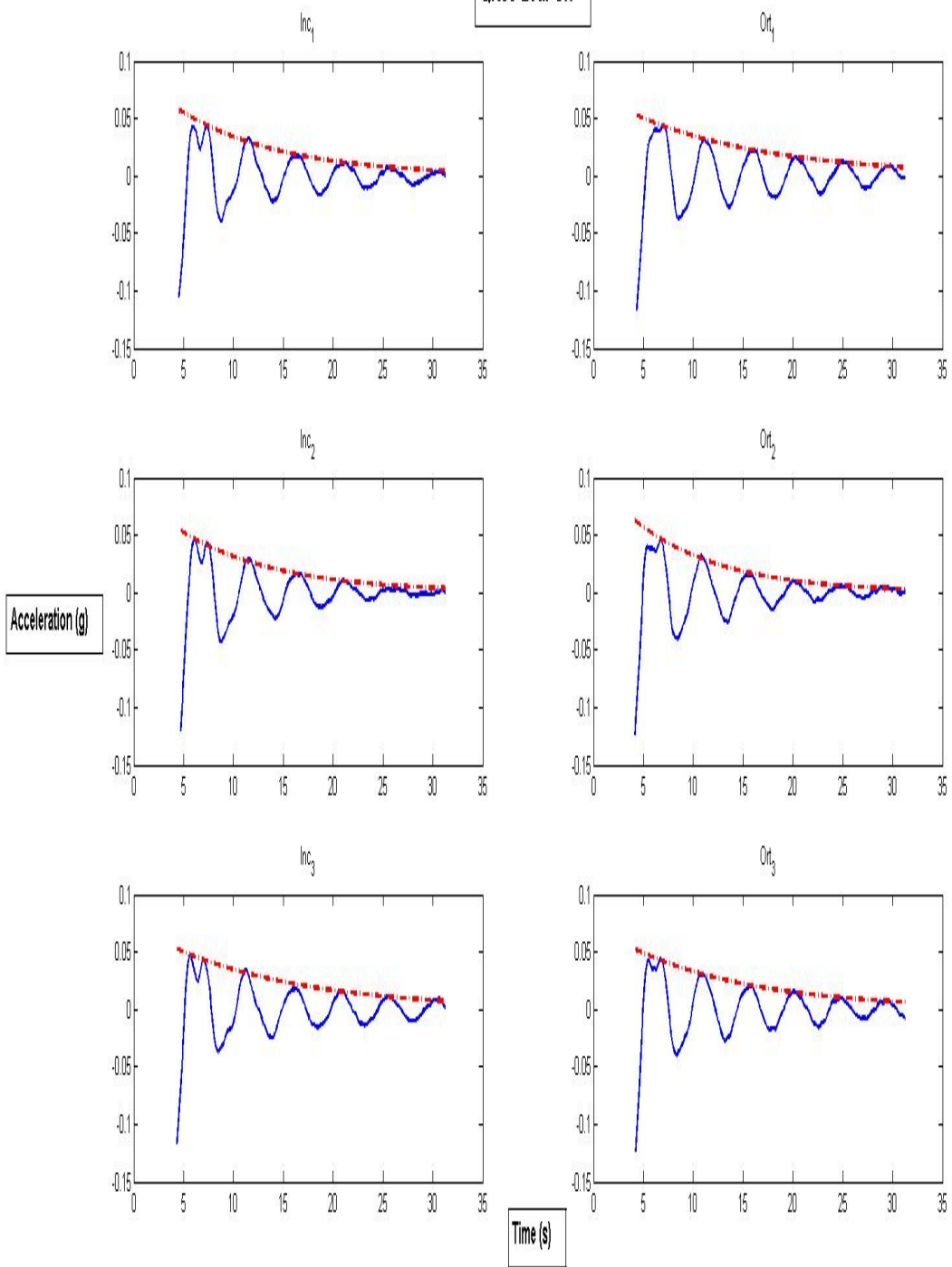
QR52 Leaf On



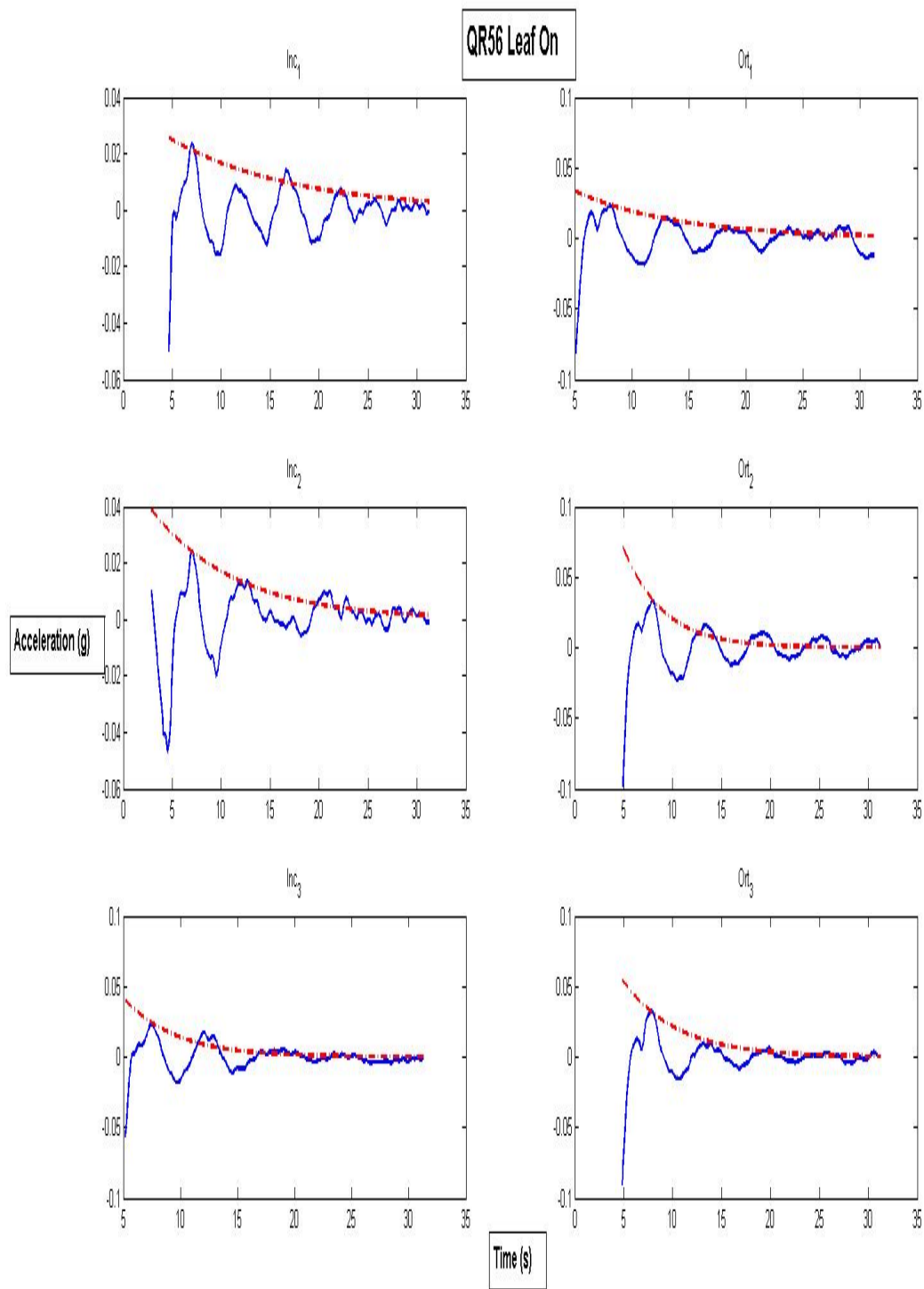


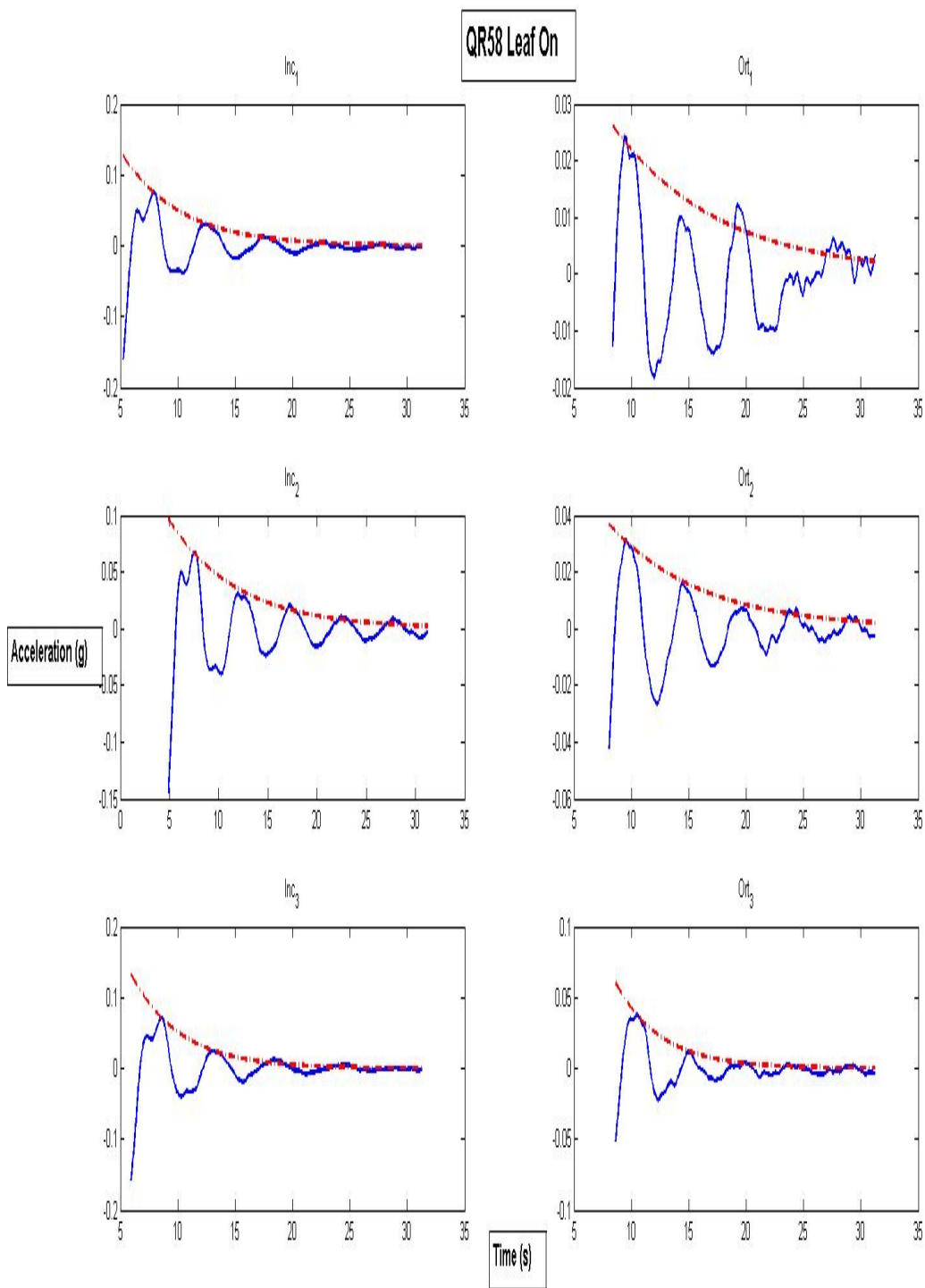


QR55 Leaf On

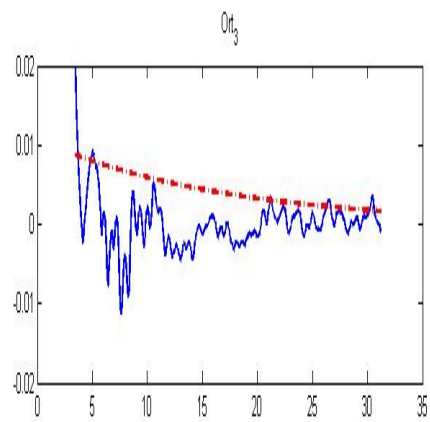
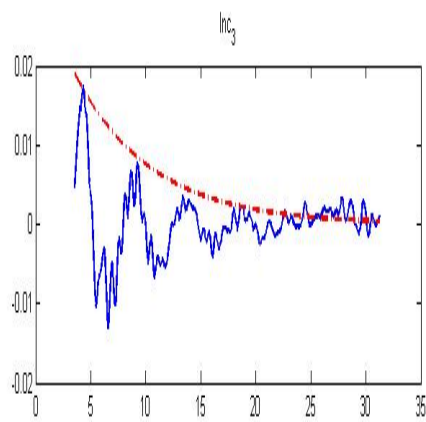
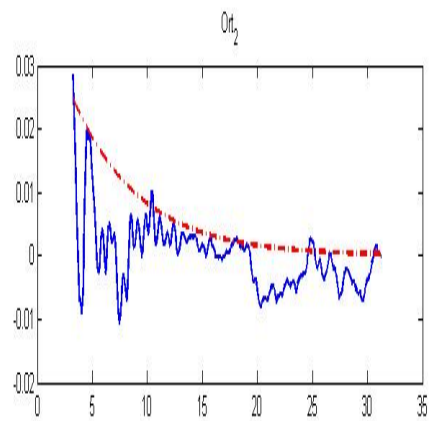
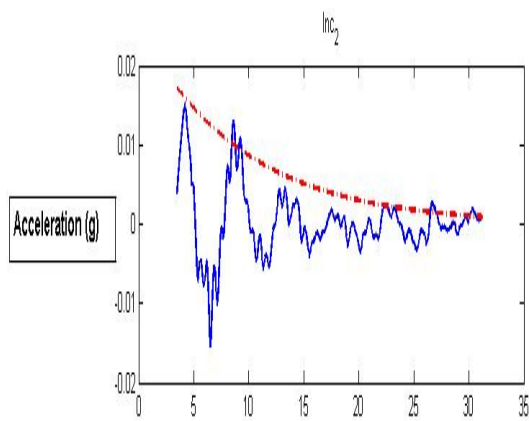
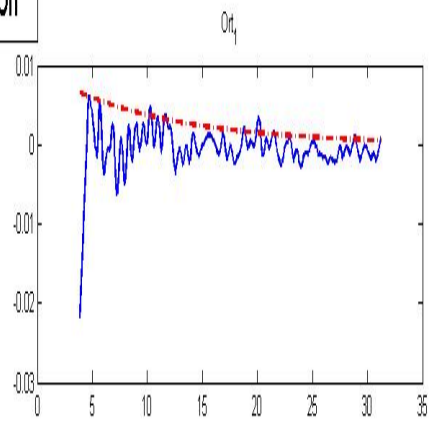
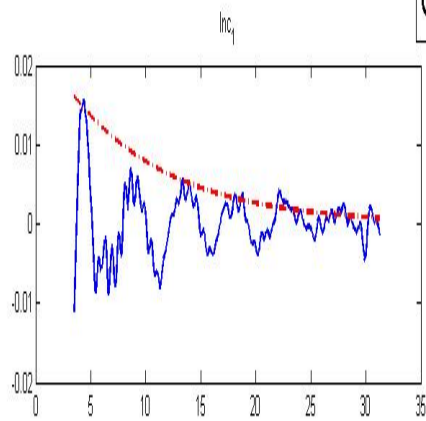






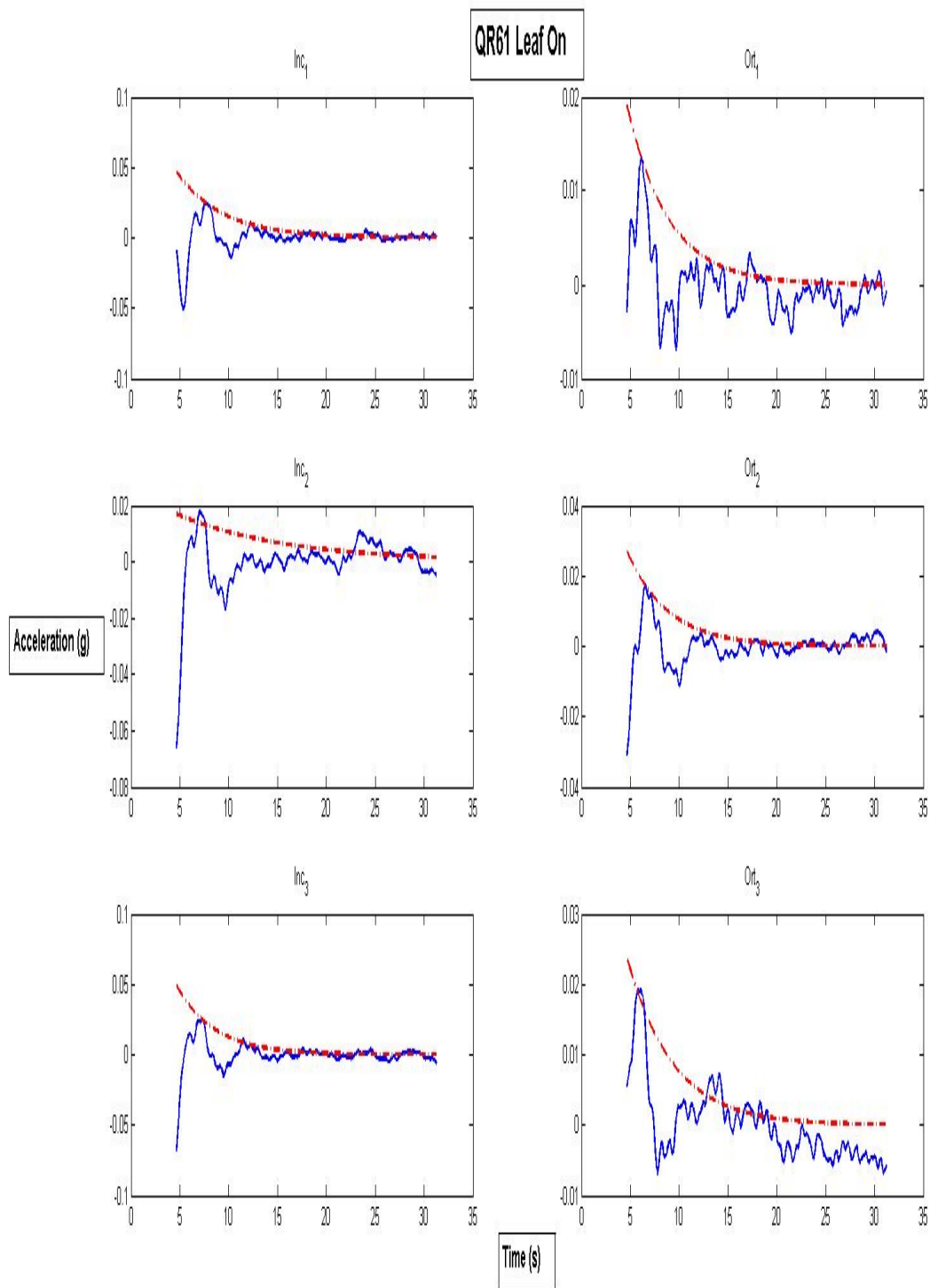


QR59 Leaf On



Acceleration (g)

Time (s)



## APPENDIX C

### MORPHOLOGICAL AND MEASURED CHARACTERISTICS OF SAMPLE TREES

Tree	Index	DBH (cm)	Height (m)	Cable	Cable Span (m)	Cable Height (m)	Tension (N)	Height to Co-Dominant (m)	Stiffness (N*m <sup>2</sup> )	Frequency (Hz)		Damping Ratio (%)	
										Leaf Off	Leaf On	Leaf Off	Leaf On
50	a	43.9	18.3	N	1.1	16.2	NA	12.4	1.06E+07	0.28	0.23	4.4%	10.9%
51	b	49	22.6	Y	2.3	19.1	17.8	12.3	1.15E+07	0.39	0.20	2.1%	7.2%
52	c	41.7	19.2	N	1	16.8	NA	11.9	5.04E+06	0.22	0.18	7.5%	10.4%
53	d	42.4	19.8	N	1.1	17	NA	11.9	7.15E+06	0.23	0.18	6.5%	17.5%
54	e	45	22.3	Y	4.5	18.6	53.5	11.1	5.30E+06	0.68	0.20	1.3%	11.4%
55	f	46.7	22.9	N	1.2	21.3	NA	18.5	2.30E+07	0.25	0.22	5.7%	6.1%
56	g	42.7	25.6	Y	2.6	21	71.3	11.9	1.10E+07	0.20	0.17	6.3%	15.2%
58	h	35.8	24.4	N	1.2	21.2	NA	14.8	2.42E+06	0.24	0.18	7.8%	15.2%
59	i	40.9	22.3	Y	3.8	18.1	59.2	9.7	1.09E+07	0.62	0.22	1.8%	8.3%
61	j	37.1	17.1	Y	1.2	14.7	44.5	9.8	4.75E+06	0.46	0.18	2.6%	18.8%

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